Diffractive Dijets and Gap Survival Probability at HERA

Sebastian Schätzel (CERN)

CERN EP Seminar
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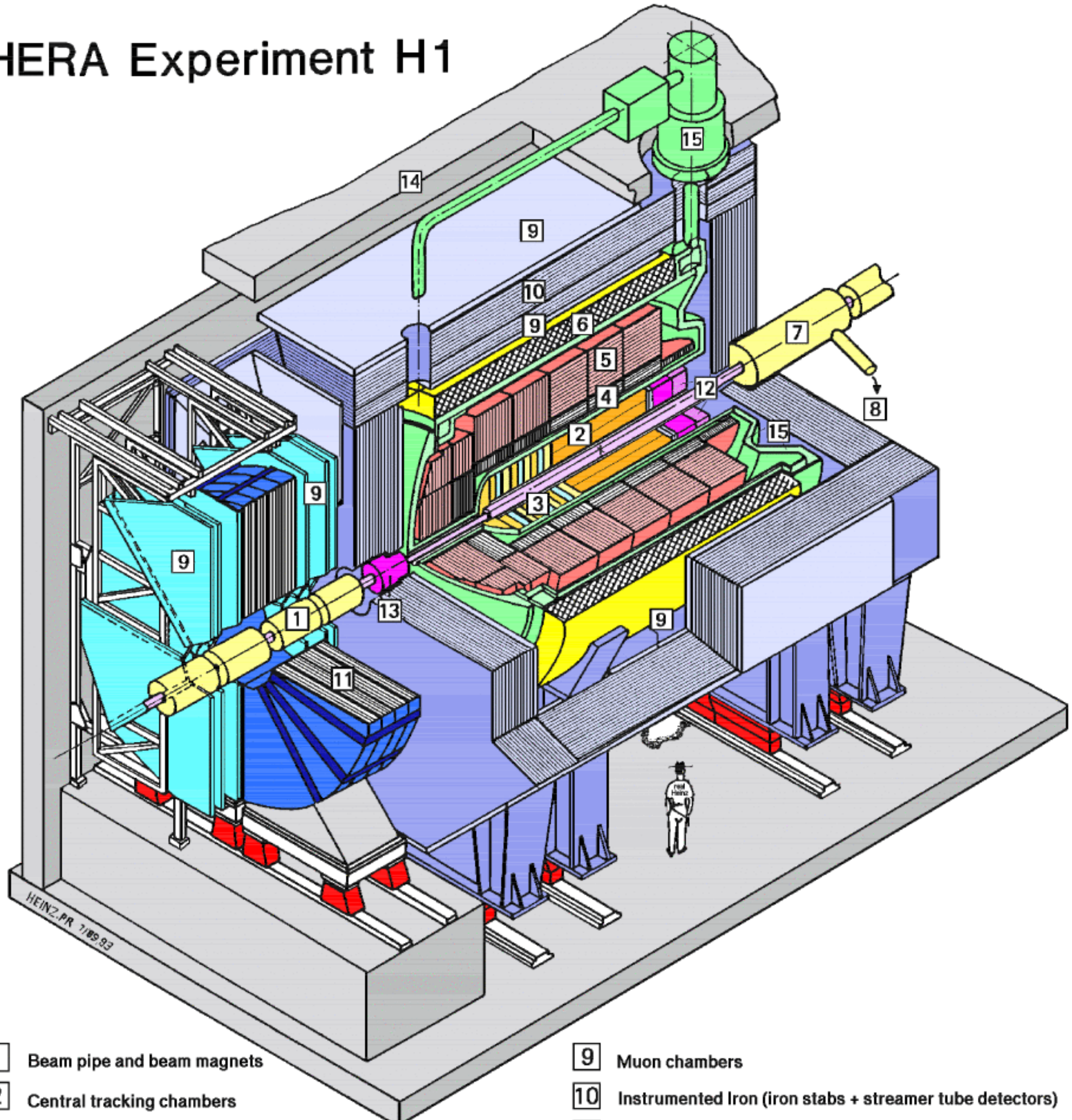
HERA Electron-Proton Collider

May 1992-June 2007, DESY Hamburg

- 27.5 GeV electrons on 820 GeV protons (920 since 1999)
- E_{cm} = 300 GeV (320)
- highlights: parton structure of proton, photon, pion, pomeron

HERA Experiment H1

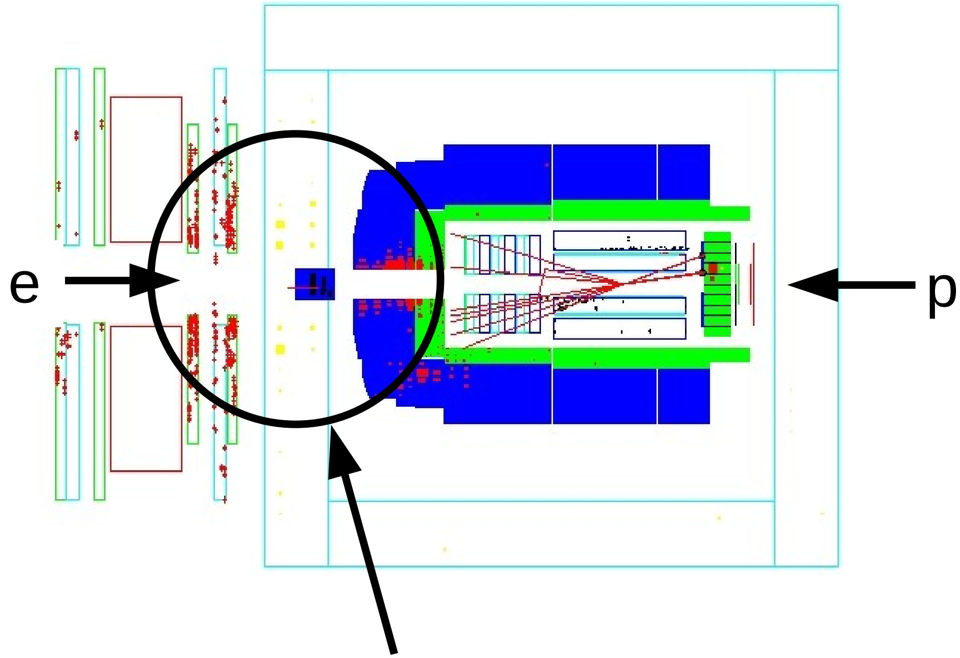


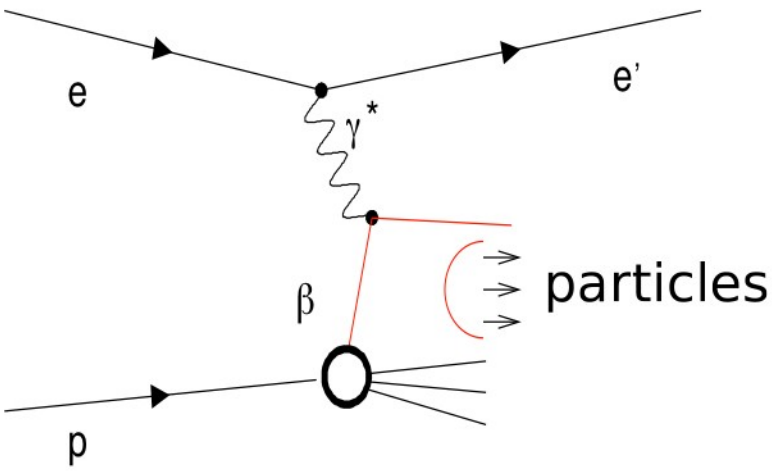
1	Beam pipe and beam magnets	9	Muon chambers
2	Central tracking chambers	10	Instrumented Iron (iron stabs + streamer tube detectors)
3	Forward tracking and Transition radiators	11	Muon toroid magnet
4	Electromagnetic Calorimeter (lead) } Liquid Argon	12	Warm electromagnetic calorimeter
5	Hadronic Calorimeter (stainless steel) } Liquid Argon	13	Plug calorimeter (Cu, Si)
6	Superconducting coil (1.2T)	14	Concrete shielding
7	Compensating magnet	15	Liquid Argon cryostat
8	Helium cryogenics		

general purpose detector
4π coverage,
asymmetric

+small "tagging" devices
for proton and electron (far
away from central detector)

Typical ep collision event





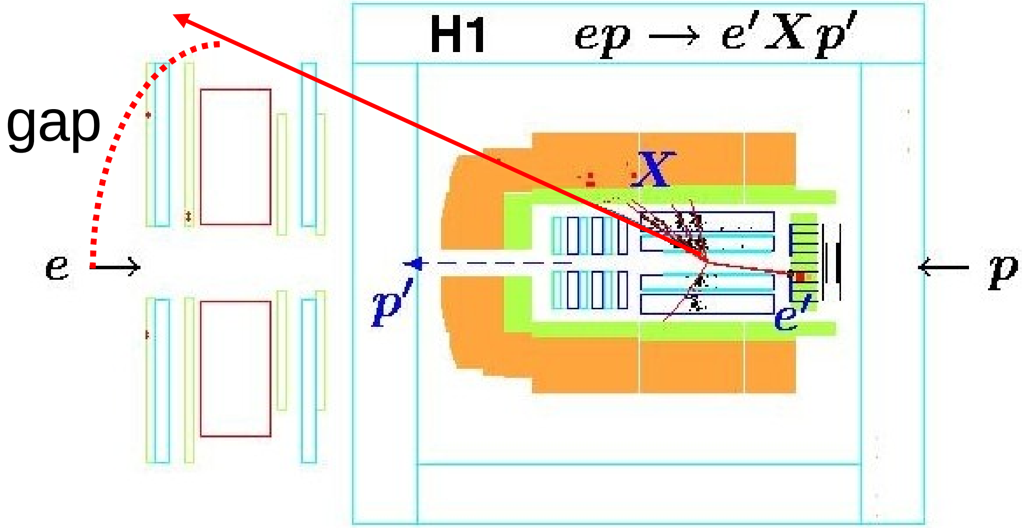
proton breaks up, many particles produced
"proton remnant"

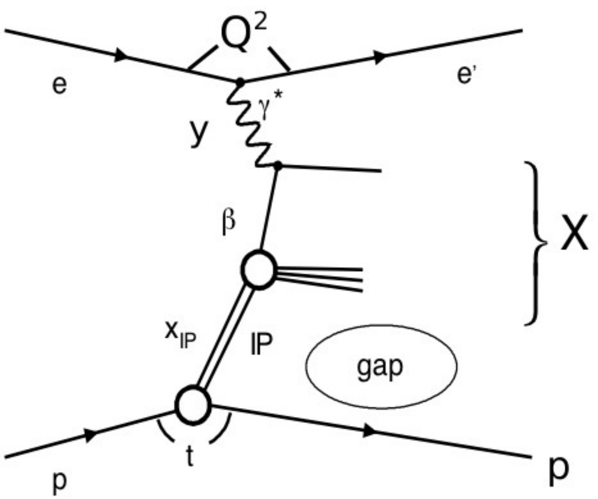
In this talk I refer to ep and γp scattering; these are also called:

ep = deep-inelastic scattering (DIS)

γp = photoproduction

...but 10% of all events look like this:





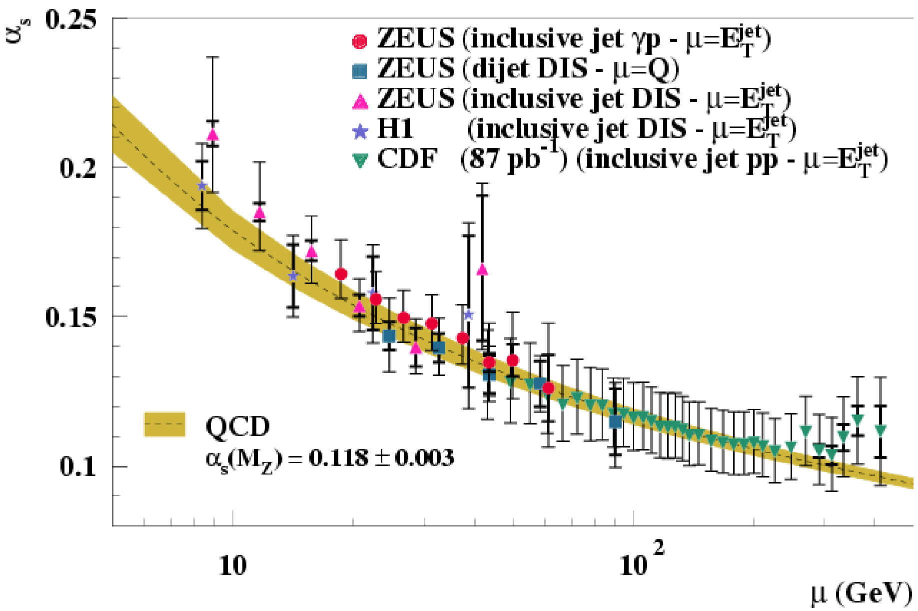
large region in detector without particles (rapidity gap)

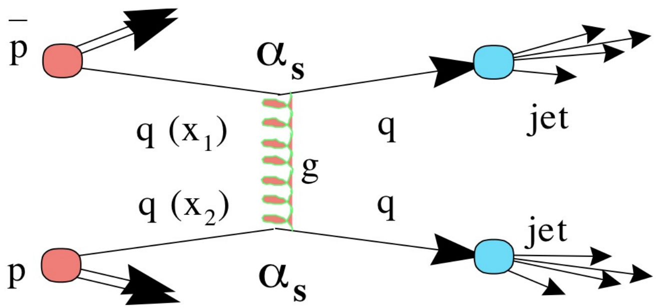
extraordinary!
- proton stays intact
- yet sizable activity in central detector

...but known from pp scattering...

Proton-Proton Scattering

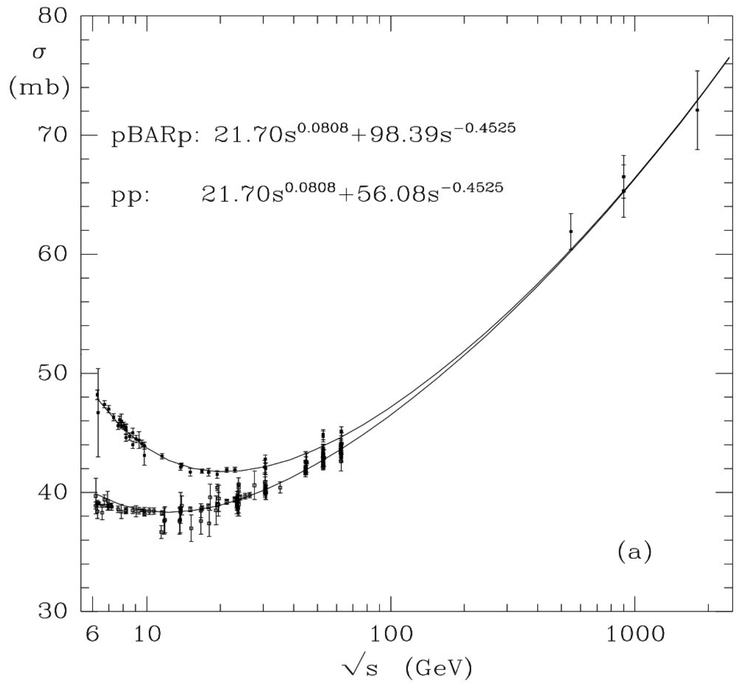
- predictions of perturbative QCD limited to “hard” parton scattering
- with it can calculate only <1% of the total pp cross section!

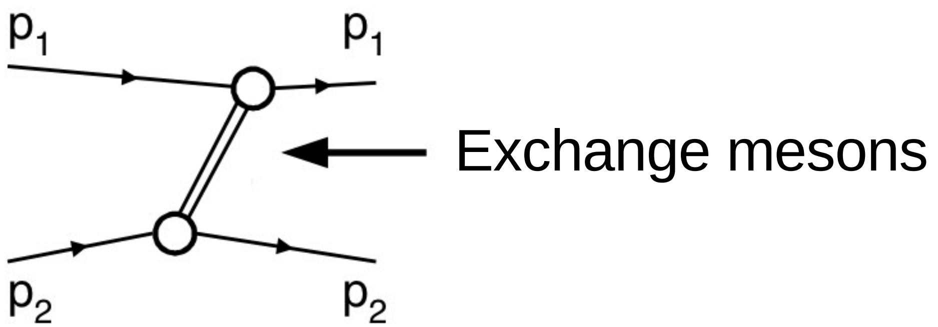




pp scattering is ~entirely “soft” collisions, hadrons interact as a whole
→ need pre-QCD theory (Regge)

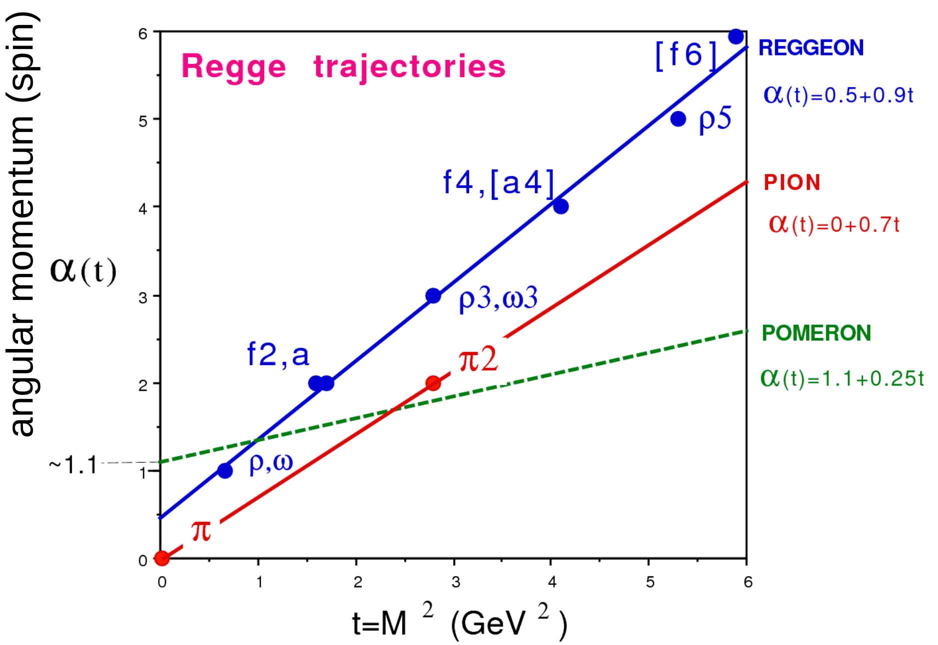
Regge Theory





$$\sigma_{tot} \sim s^{\alpha(0)-1}$$

$$\alpha_{IP}(0)=1.08$$



introduce pseudo-particle
“Pomeron” to explain
rise at high s

Isaak Pomeranchuk

(1913-1966)

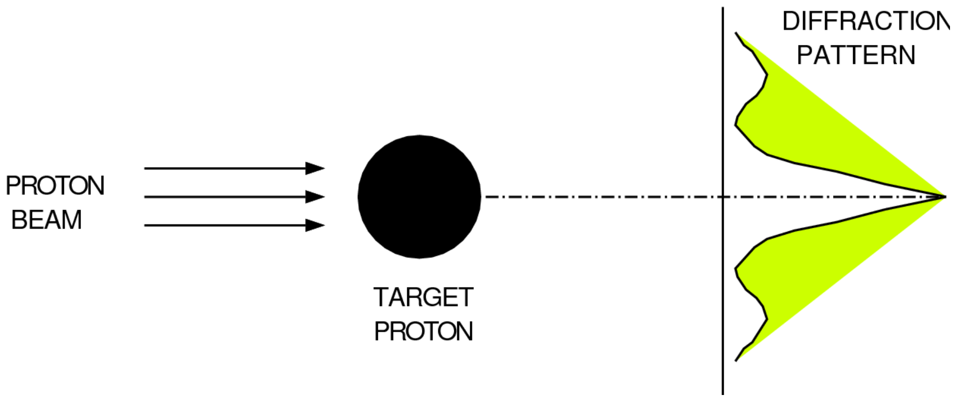
fundamental theorems of
high energy scattering

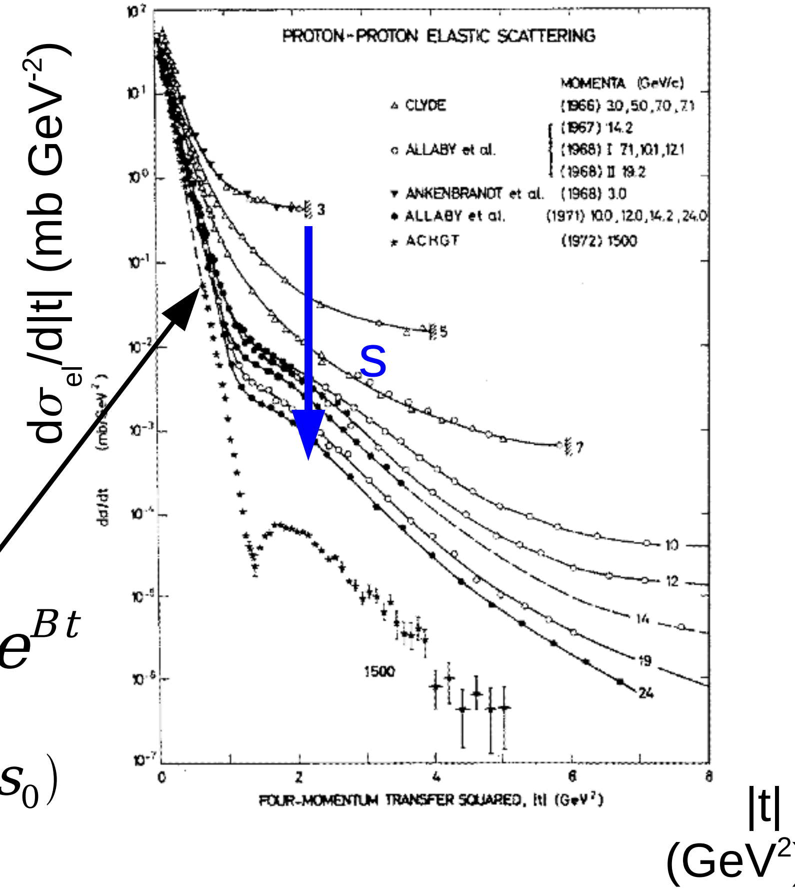
the “Pomeron” was named after him

Why “Diffraction”?

PROTON-PROTON ELASTIC SCATTERING

from K. Goulianos





$$\frac{d\sigma_{el}}{dt} \propto e^{Bt}$$

$$B = 2\alpha' \ln(s/s_0)$$

connected with σ_{tot} through optical theorem

t=square of transferred 4-momentum

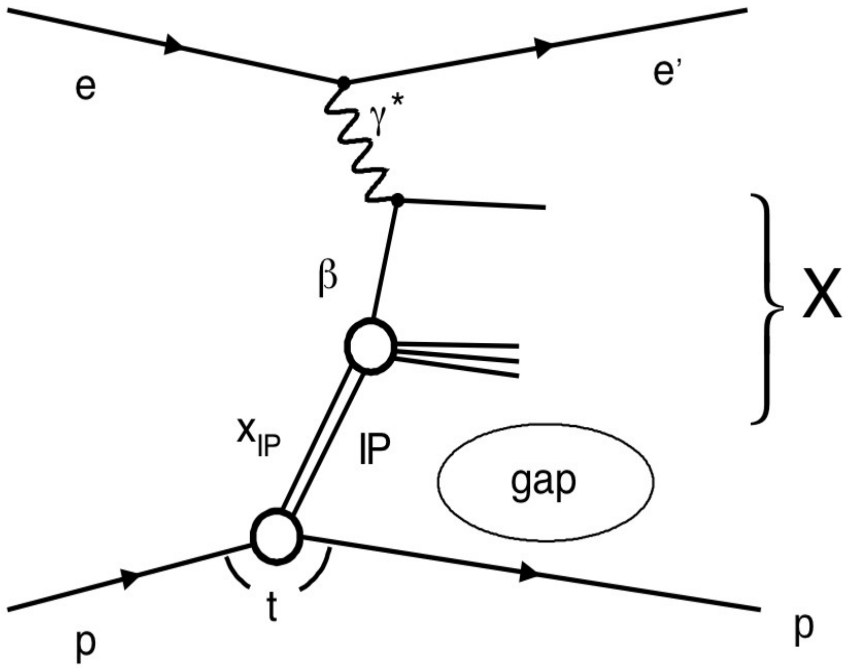
A Pomeron at HERA?
Let's study the structure!

- it is indeed a pomeron: analysis yields $\alpha_{IP}(0)=1.111(7)>1$ [larger than 1.08! different pomeron?]

- we are lucky: HERA is the ideal place to study the parton structure

- Determine structure just like normal proton structure, but use diffractive events

Kinematics



Q^2 photon virtuality, -(4-momentum)^2

β quark momentum fraction

Diffractive variable:

$x_{I\!P}$ fractional proton momentum loss

small in diffraction, O(%)

rapidity gap $\Delta\eta \sim \ln(1/x_{I\!P})$

typically >3.5

$$x = x_{I\!P}\,\beta$$

$$Q^2 = s\,x\,y$$

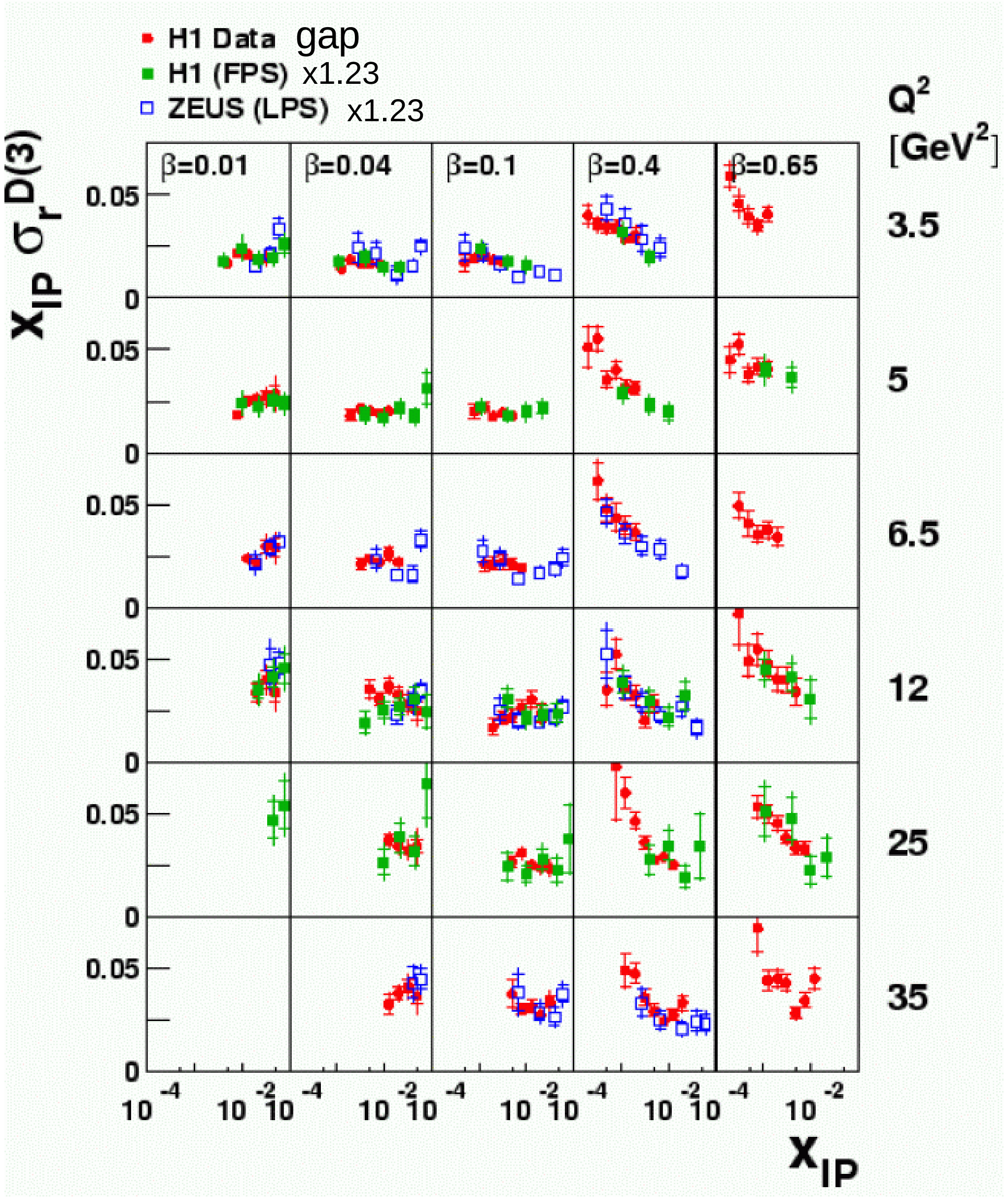
pseudorapidity $\eta = -\ln(\tan\frac{\theta}{2})$

θ =polar scattering angle

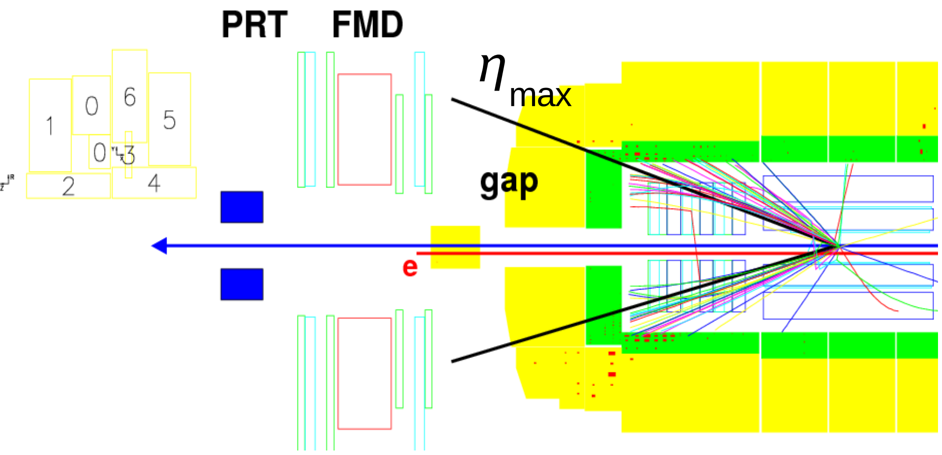
Selecting diffractive events

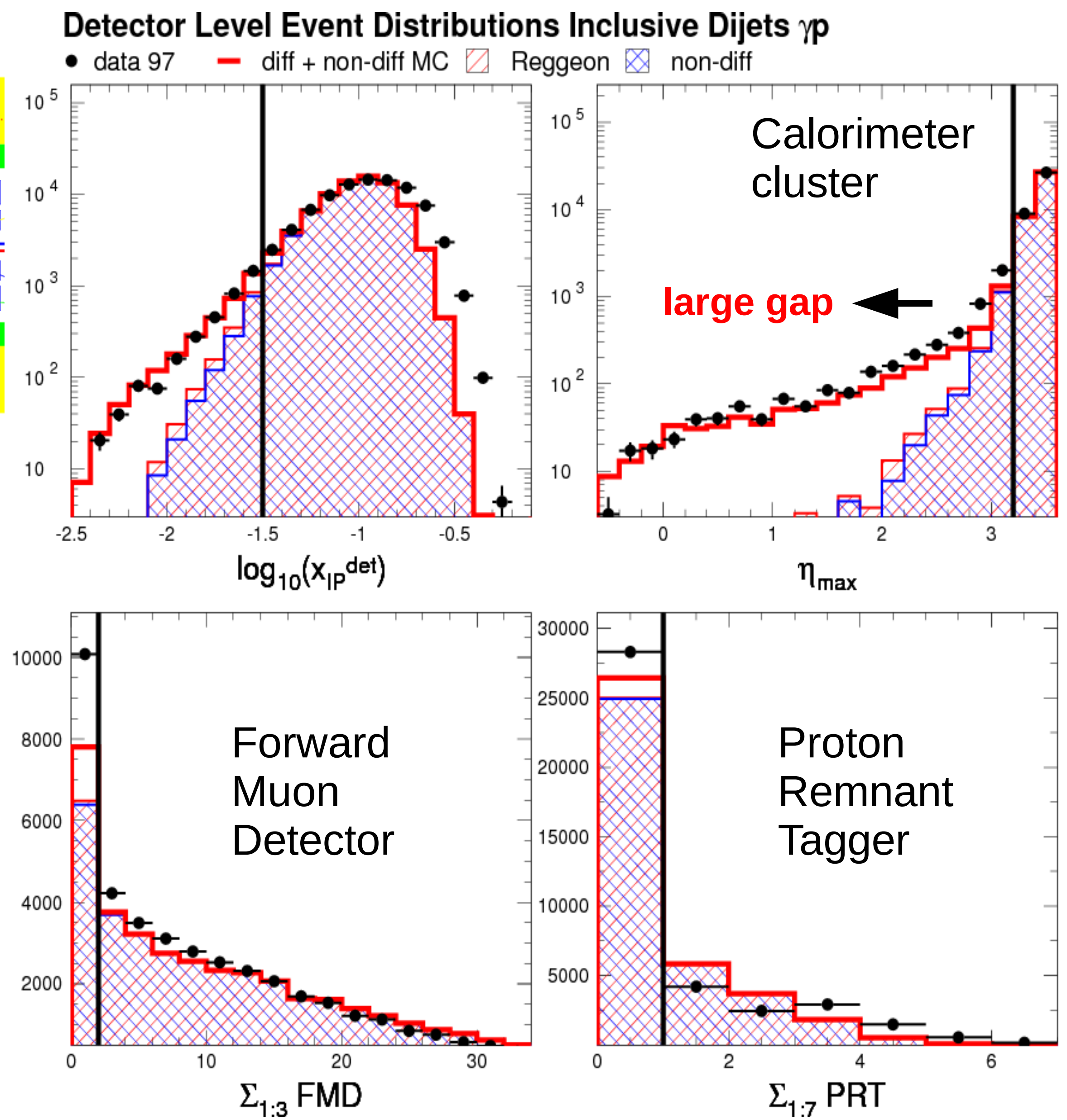
- proton tagging
  - Roman pots, low acceptance/statistics
  - measure t dependence: B=5..8 GeV^{-2}
- rapidity gap
  - $|t|<1$ GeV^2
  - ≈25% proton dissociation with mass≲2 GeV

the two methods give consistent results (also across experiments)



“Gap Selection” of diffractive events





normal triggers + require empty forward detectors

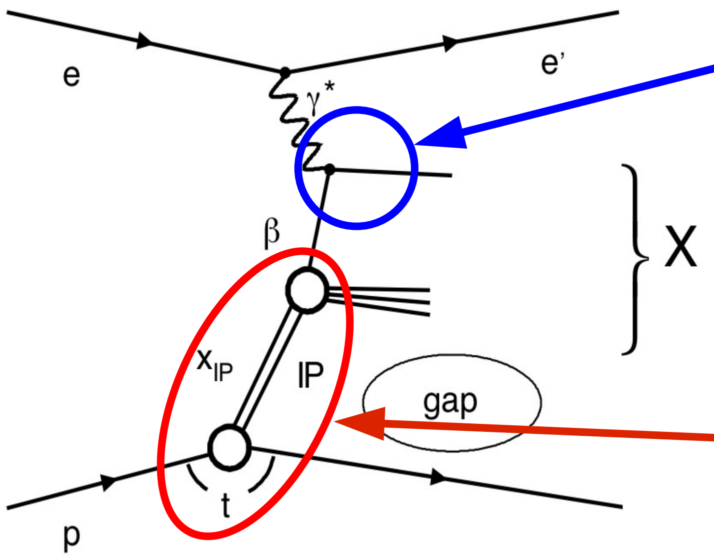
“H1 forward instrumentation like a Swiss cheese” *F. Eisele*

Monte Carlo not perfect

→ important systematic error

QCD Factorisation

proof for diffraction (in the presence of a hard scale):
John Collins



$$\sigma_D^{\gamma^* p} = \sum_{\text{partons } i} f_{i/p}^D \otimes \sigma^{\gamma^* i}$$

parton densities
- soft, not calculable in pQCD
- have to extract them from measurement
- process-independent!

Fitting for Parton Densities

$$\frac{d^4\sigma^{ep}_D}{d\beta\; dQ^2\; dx_{IP}\; dt} \propto F_2^{D(4)}\left(\beta, Q^2, x_{IP}, t\right)$$

form factor (“structure function”): $F_2^D \propto \beta \sum_i e_i^2 q_i^{LO}(\beta, Q^2, x_{IP}, t)$

only quark densities!
(photon does not see gluon)

- Parameterise densities at a starting scale Q_0^2=2 GeV^2
- evolve densities to measured scale using DGLAP equations at NLO
- fit measured cross section

gluon radiation, splitting

phenomenological Ansatz

needed because not enough data to fit separately for every x_{IP}, t point

$$f_i^D(\beta, Q^2, x_{I\!P}, t) = f_{I\!P}(x_{I\!P}, t)\, f_{i/I\!P}(\beta, Q^2)$$

$$f_{I\!P} \propto \frac{e^{Bt}}{x_{I\!P}{}^{2\alpha_{I\!P}(t)-1}}$$

describes data well
$\alpha_{IP}(0)$=1.111(7)

Inclusive cross section and fit

- measure quarks directly

$$F_2^D \sim \beta \sum_i e_i^2 \; q_i^{LO}$$

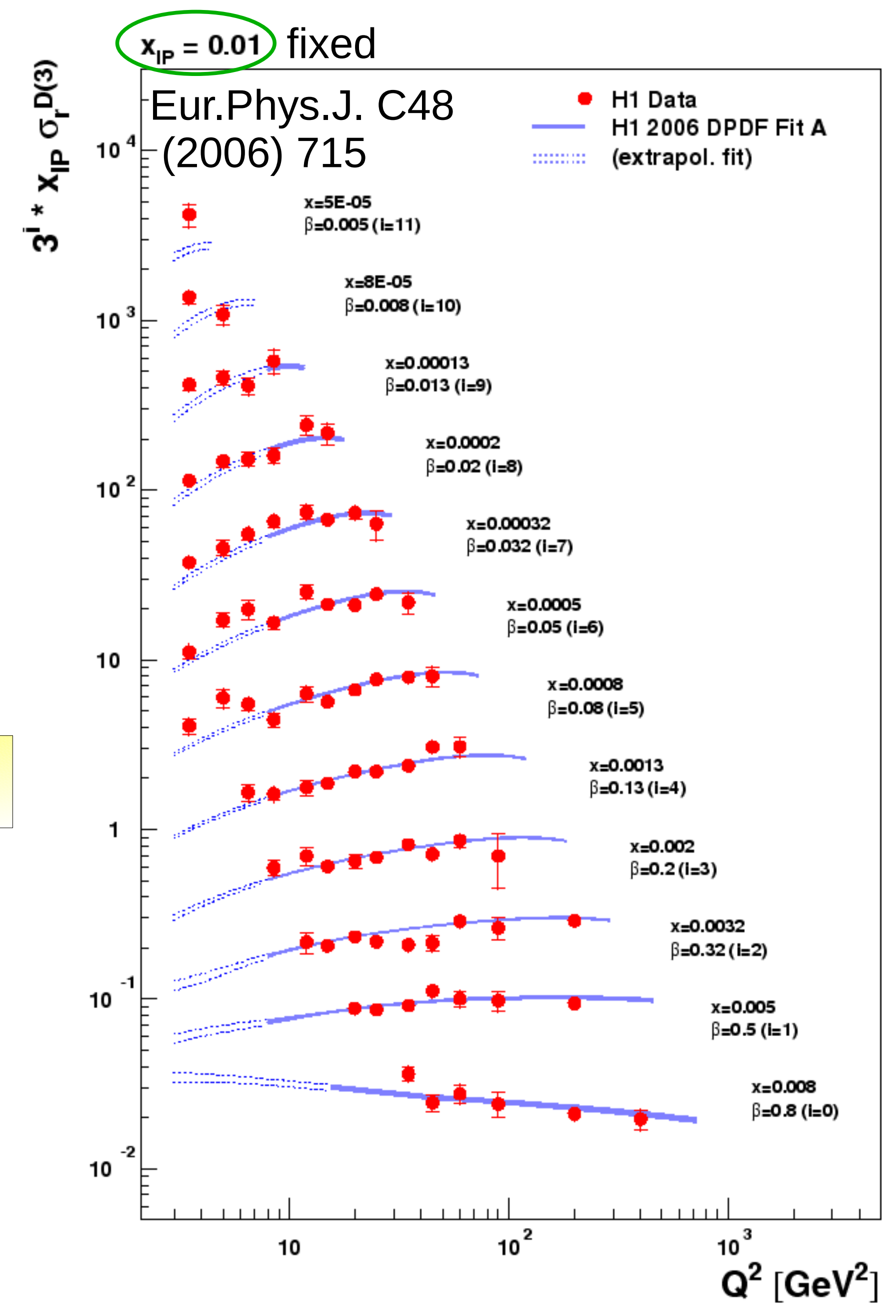
- gluon from scaling violations

$$\partial F_2^D / \partial \ln Q^2 \sim \alpha_s \, g^{LO}$$

positive scaling violations up to $\beta \approx 0.6$

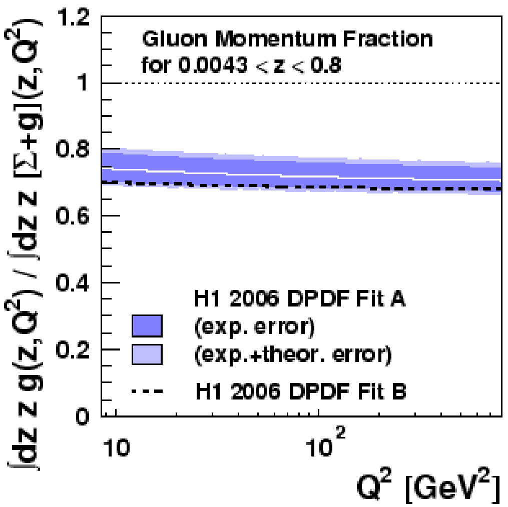
ordinary F_2 rises up to $x_{Bj} \approx 0.1$

large gluon component



Diffractive Parton Densities

- gluon carries 70% of momentum



- 2 different gluons (Fit A and B) describe inclusive diffraction equally well

➡ little sensitivity to gluon at z≳0.5
(too few data points to fit a slope)

$$\sum = u + d + s + \bar{u} + \bar{d} + \bar{s}$$

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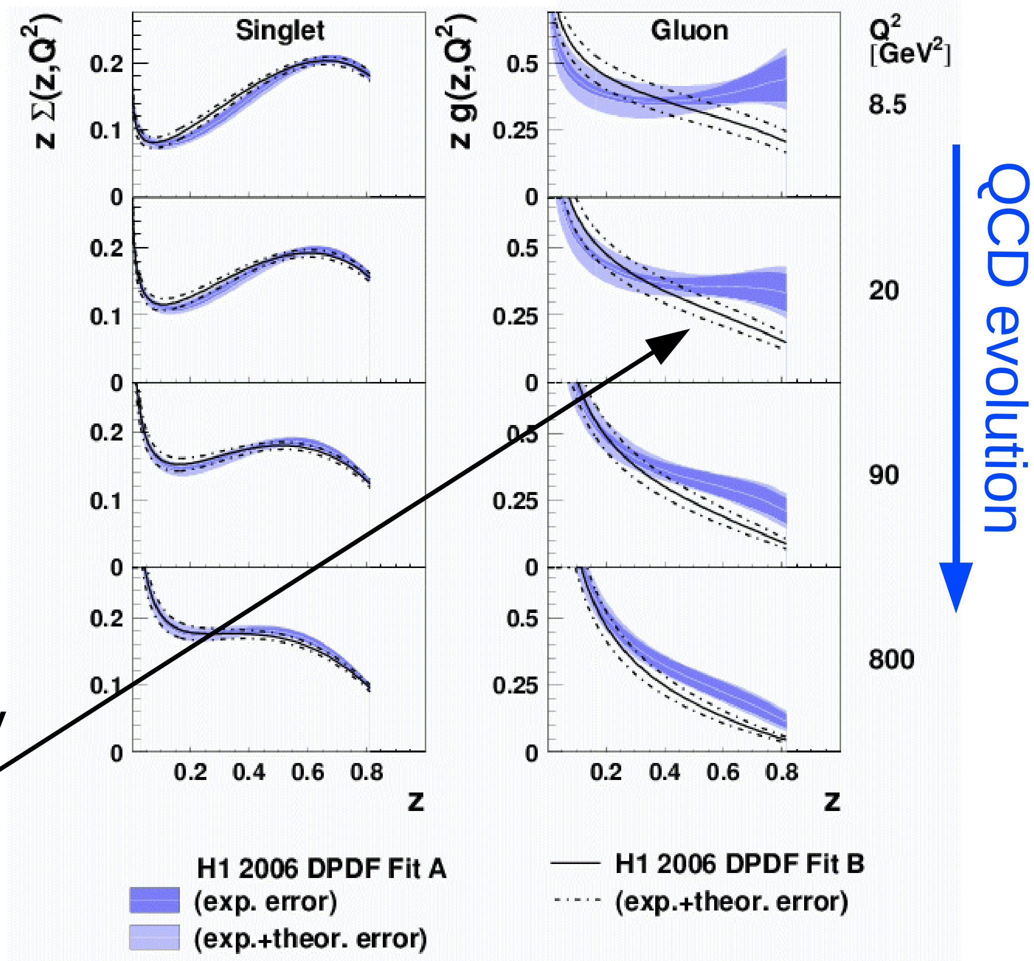
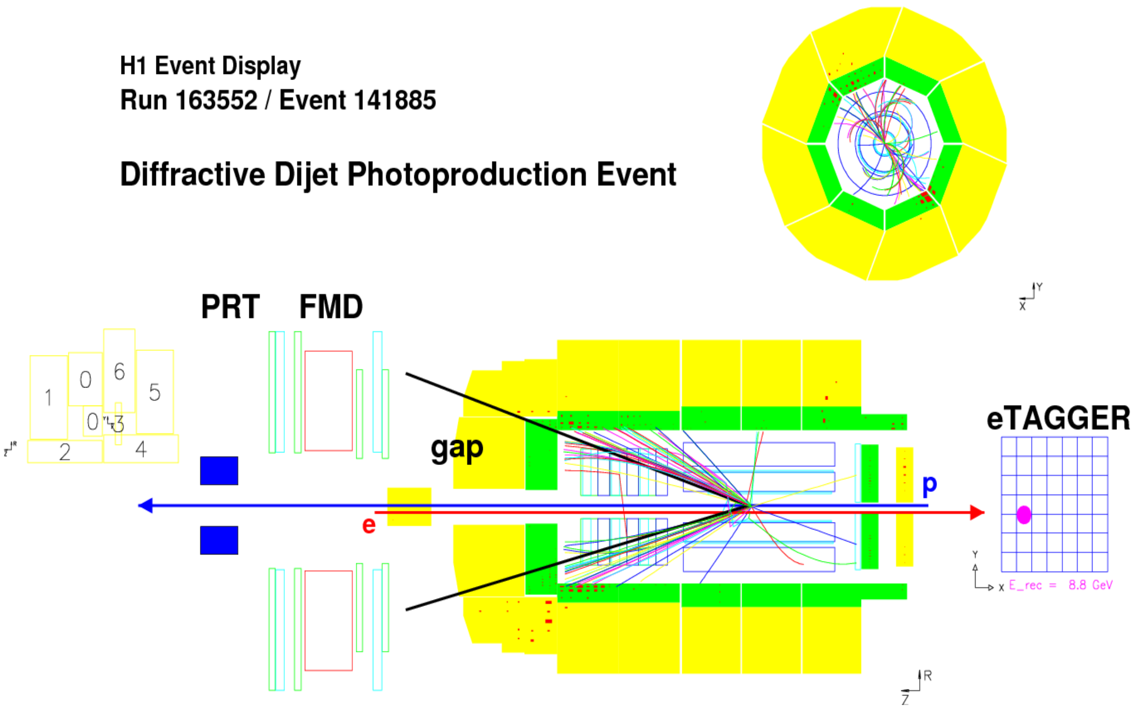
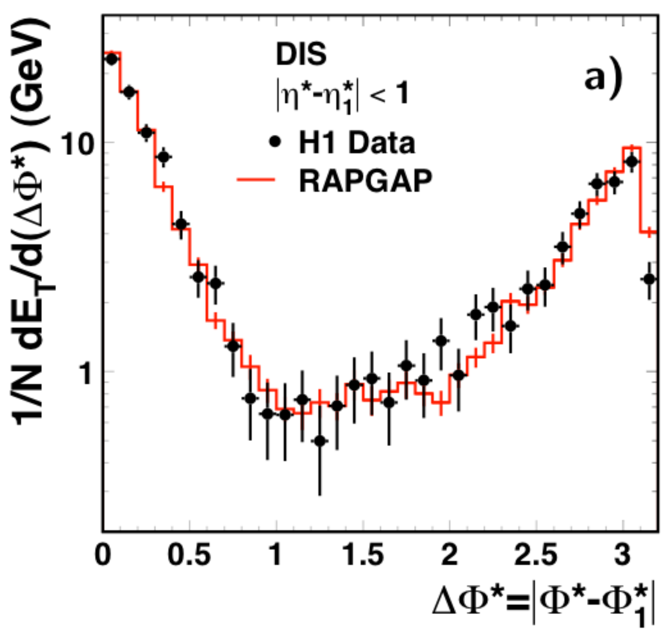


Is this diffractive proton structure universal?

- parton densities **expected** to be universal
- **test** if different processes are described by the same densities ("factorisation tests")

Diffractive Dijets





- energy flow in detector exhibits clear jet profiles with back-to-back structure
- jets reconstructed by combining track and calorimeter cluster information
- all cross sections are quoted at the level of stable hadrons (detector effects are corrected)

Diffractive Dijets in ep collisions

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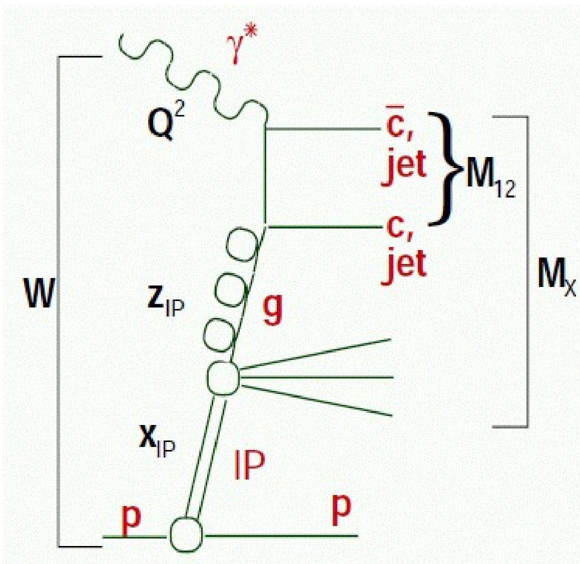
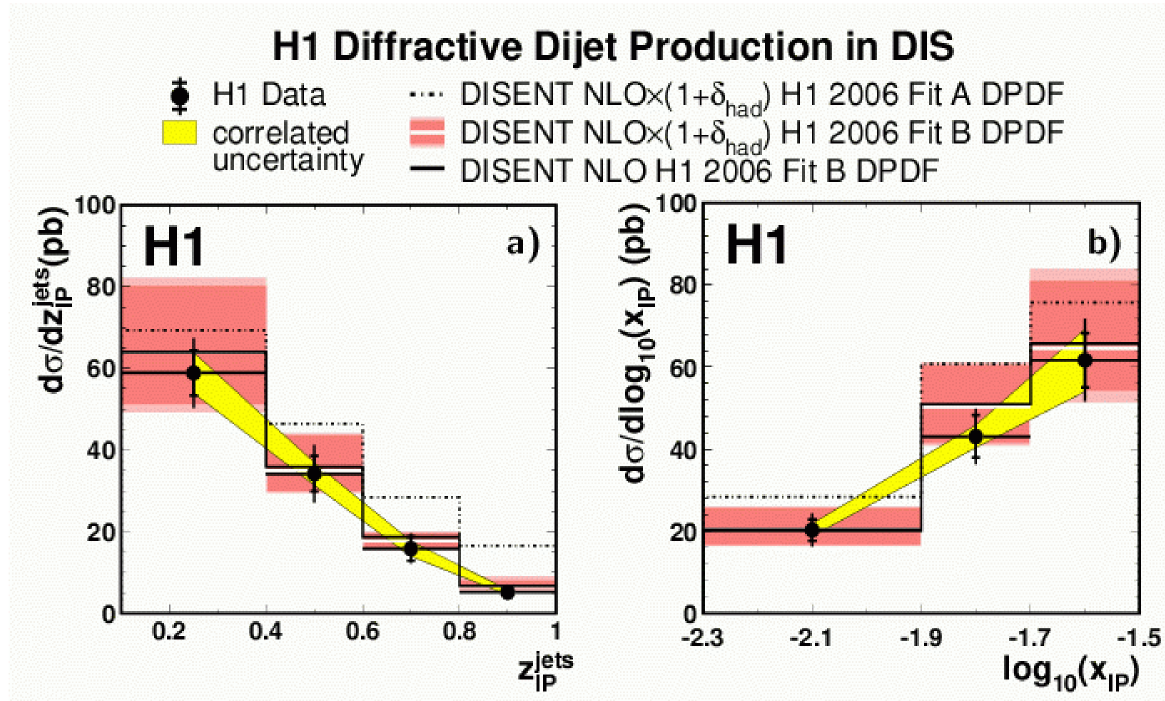
$E_T(1)>5$ GeV, $E_T(2)>4$ GeV
$4<Q^2<80$ GeV^2, $x_{IP}<0.03$
$165<W<242$ GeV, 18 pb^{-1}





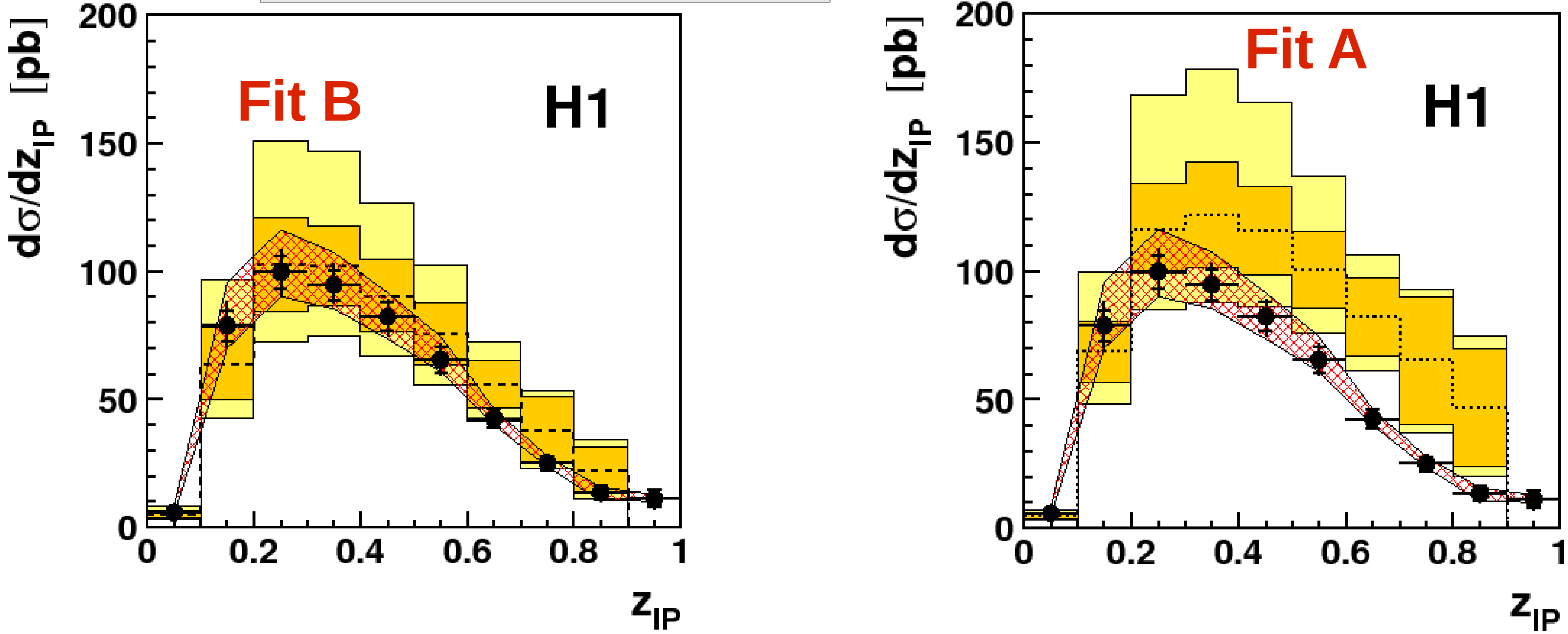
-directly sensitive to gluon
-NLO calculations: private diffractive extension of DISENT
-largest uncertainty: NLO “scale uncertainty”, scale varied by *2, /2

- QCD factorisation holds!
- dijets clearly favour Fit B

Dijets in ep collisions – latest analysis

$E_T(1)>5.5$ GeV, $E_T(2)>4$ GeV
$4<Q^2<80$ GeV^2, $x_{IP}<0.03$
$0.1<y<0.7$, 52 pb^{-1}

JHEP10 (2007) 042



NLO calculation with private diffractive extension of NLOJET++

same message: factorisation holds

Combined Fit (inclusive/jets)

use high z dijet data to constrain gluon

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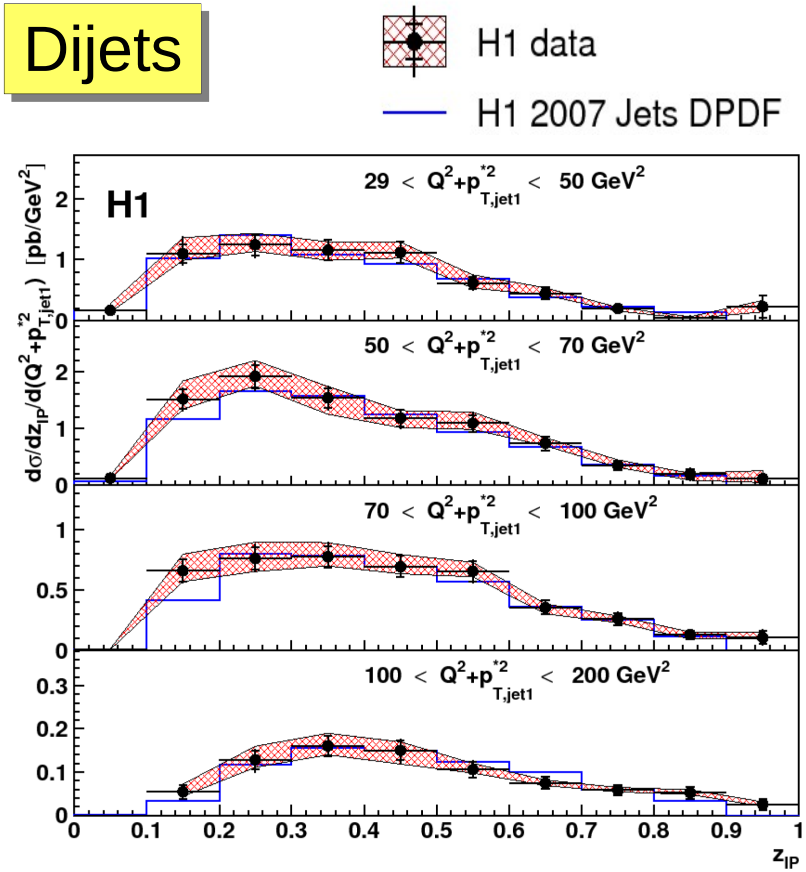
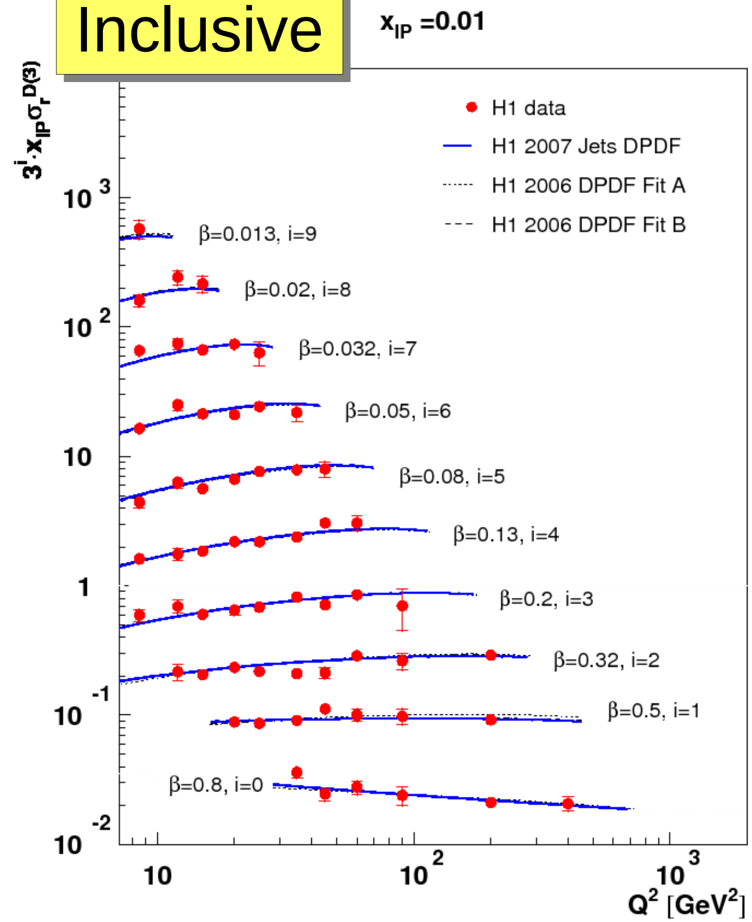
Dijets



Inclusive



good simultaneous description of jets and inclusive cross section

Gluon Density of Combined Fit

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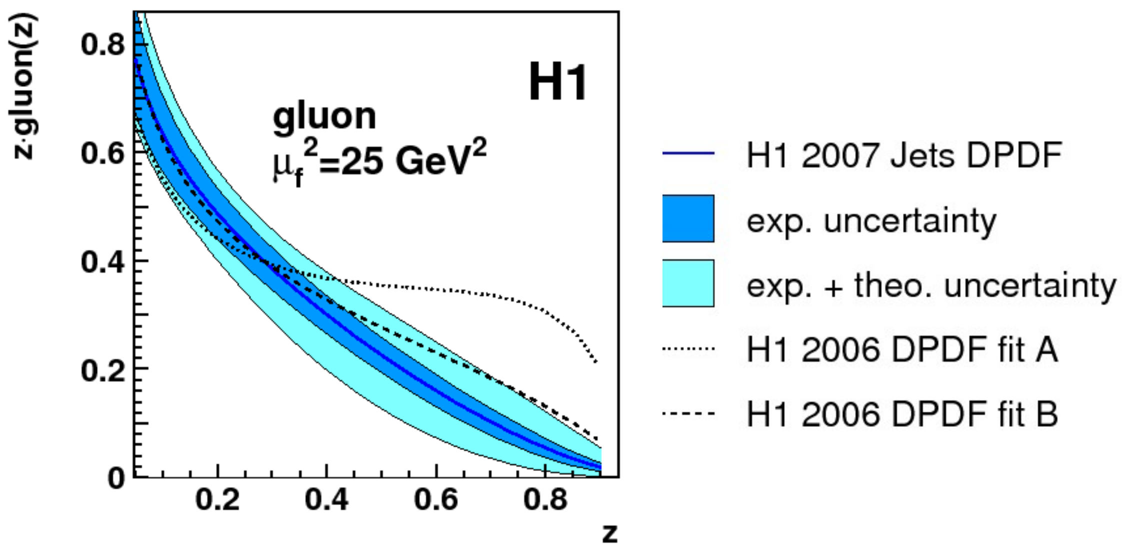
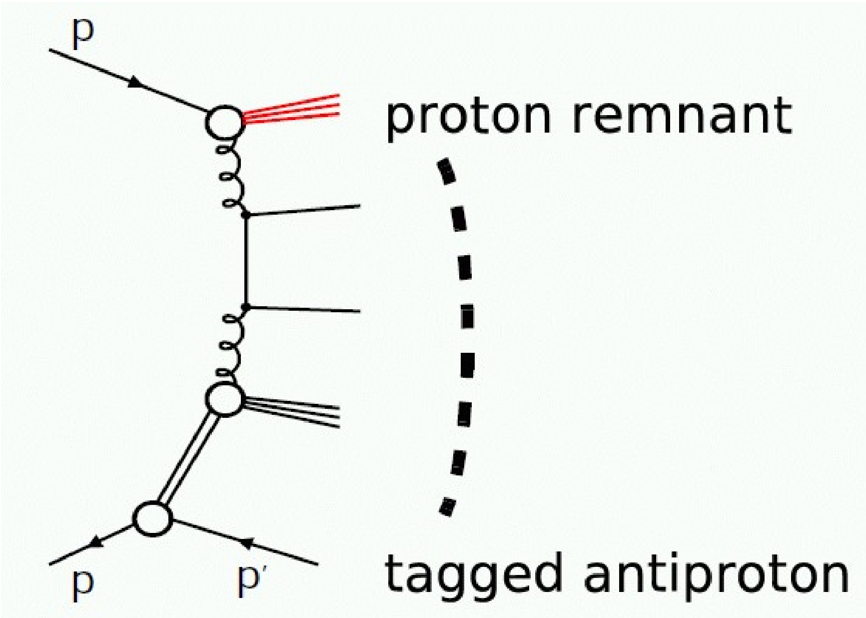


combined fit results similar to Fit B

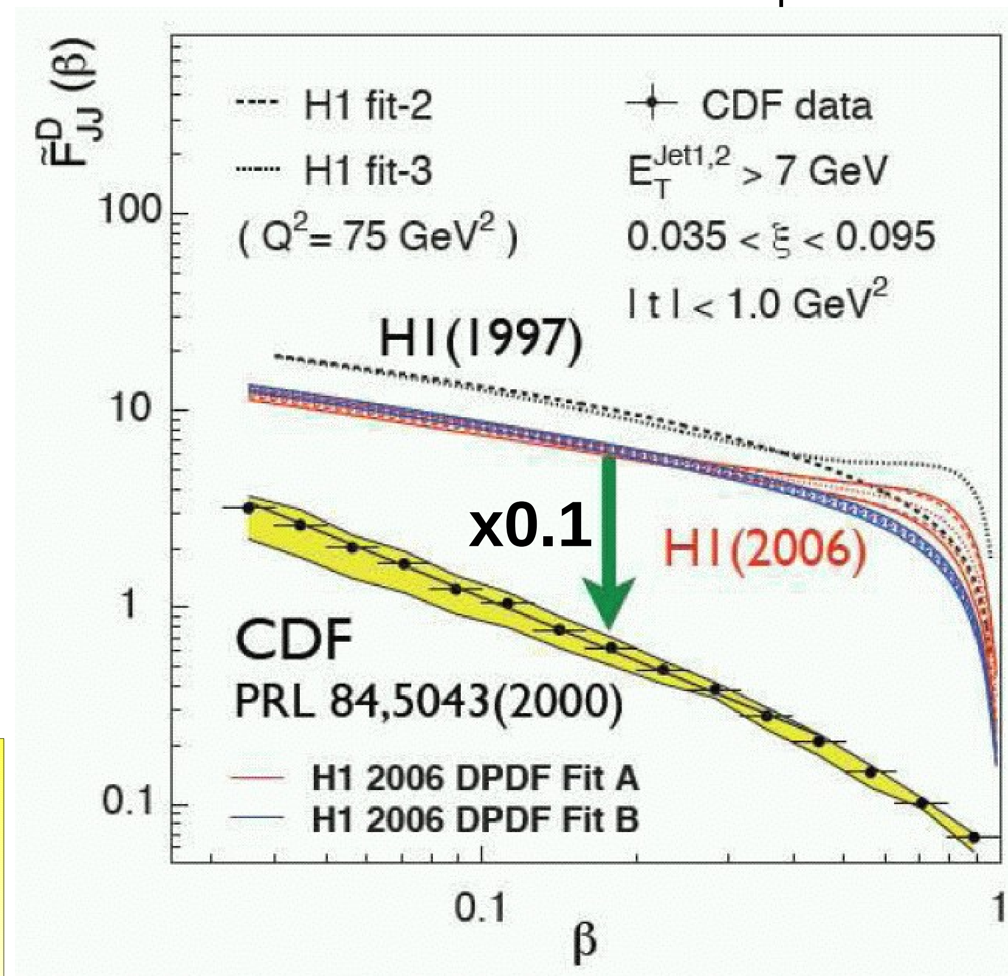
Tevatron: diffractive p$\bar{p}$ scattering



leading order comparison
with parton densities from HERA

- severe factorisation breakdown
- "gap survival probability" ≈ 0.1
- rescattering due to second proton

Diffractive structure function of antiproton



Dijet Factorisation Tests

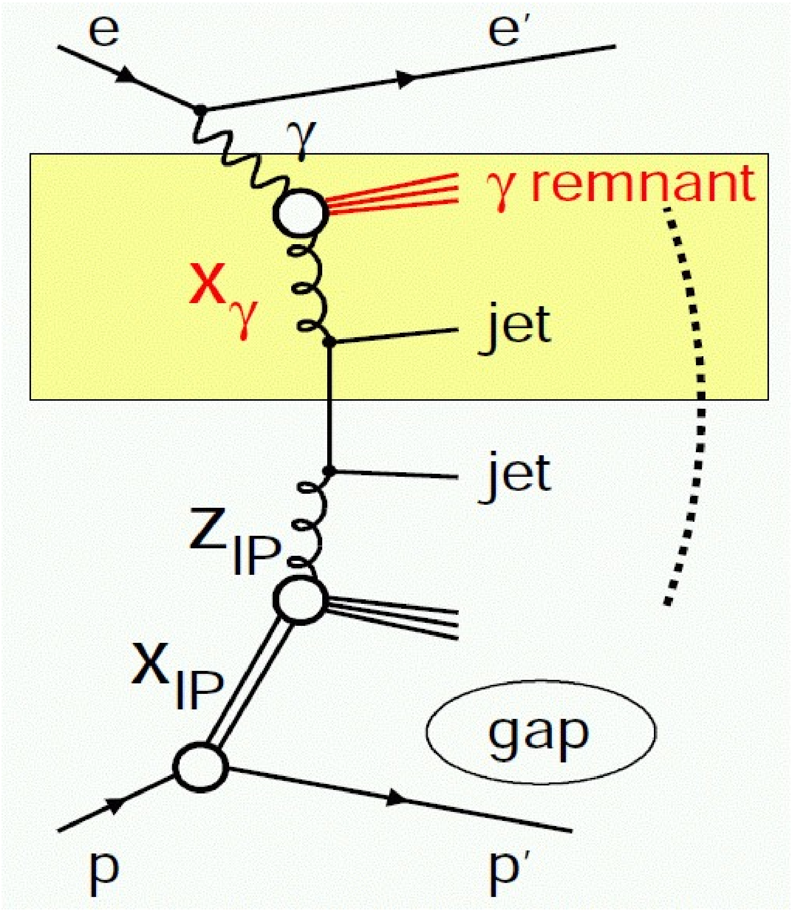
using parton densities extracted in inclusive diffractive ep scattering

	$fact^n$	gap survival probability
ep	✔	1
γp		
pp	ϟ	0.1

favours Fit B

The hadronic photon

- photon can fluctuate into a hadronic system, of which one parton with momentum fraction x_γ enters the hard scatter
- suppressed with increasing photon virtuality Q



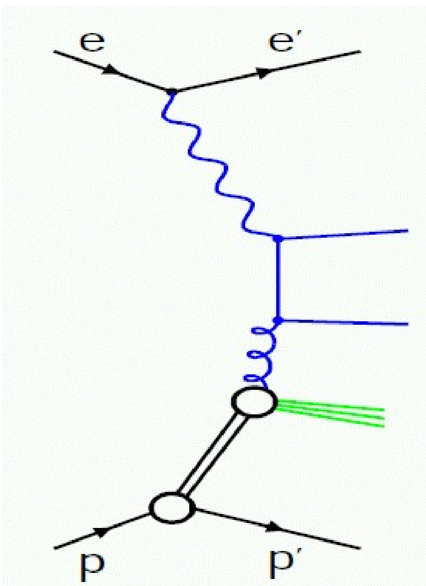
x_γ<1: photon remnant

x_γ≈1: no remnant

Does the photon remnant destroy the gap?

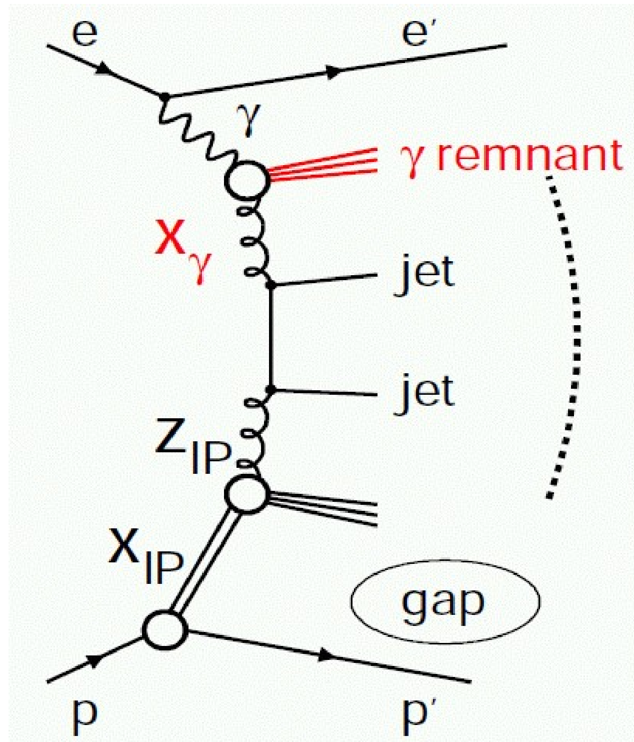
γp: The transition from ep to pp

ep



Factorisation works

γp

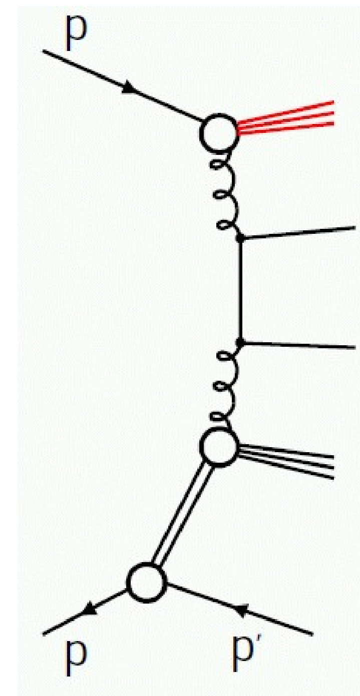


$x_\gamma < 1$: photon remnant

$x_\gamma \approx 1$: no remnant

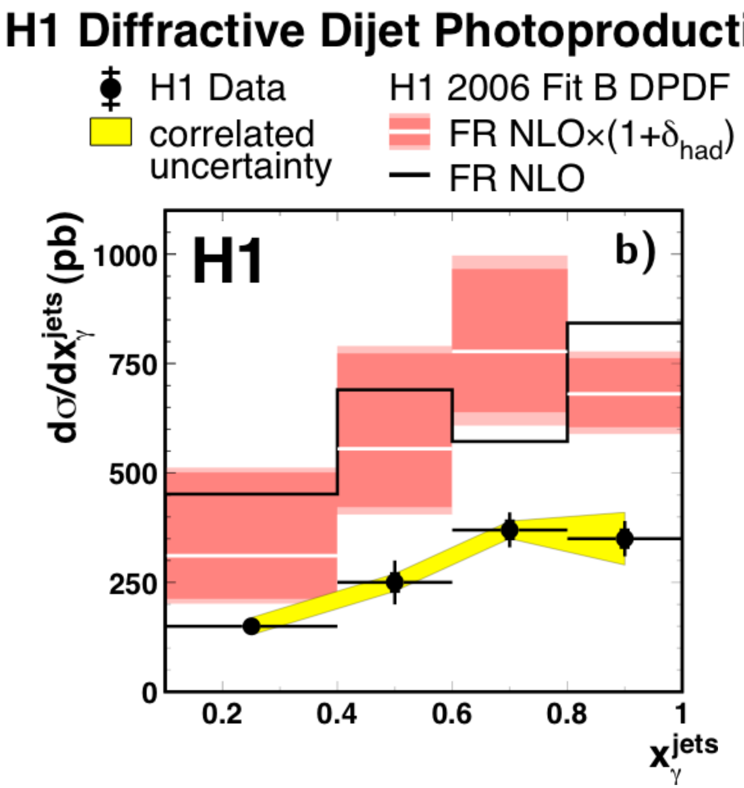
Factorisation?

$p\bar{p}$



proton remnant

Factorisation broken



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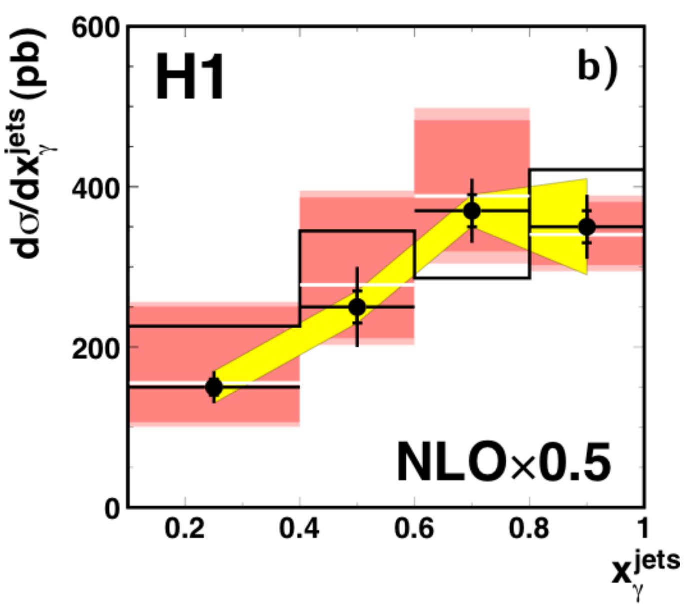
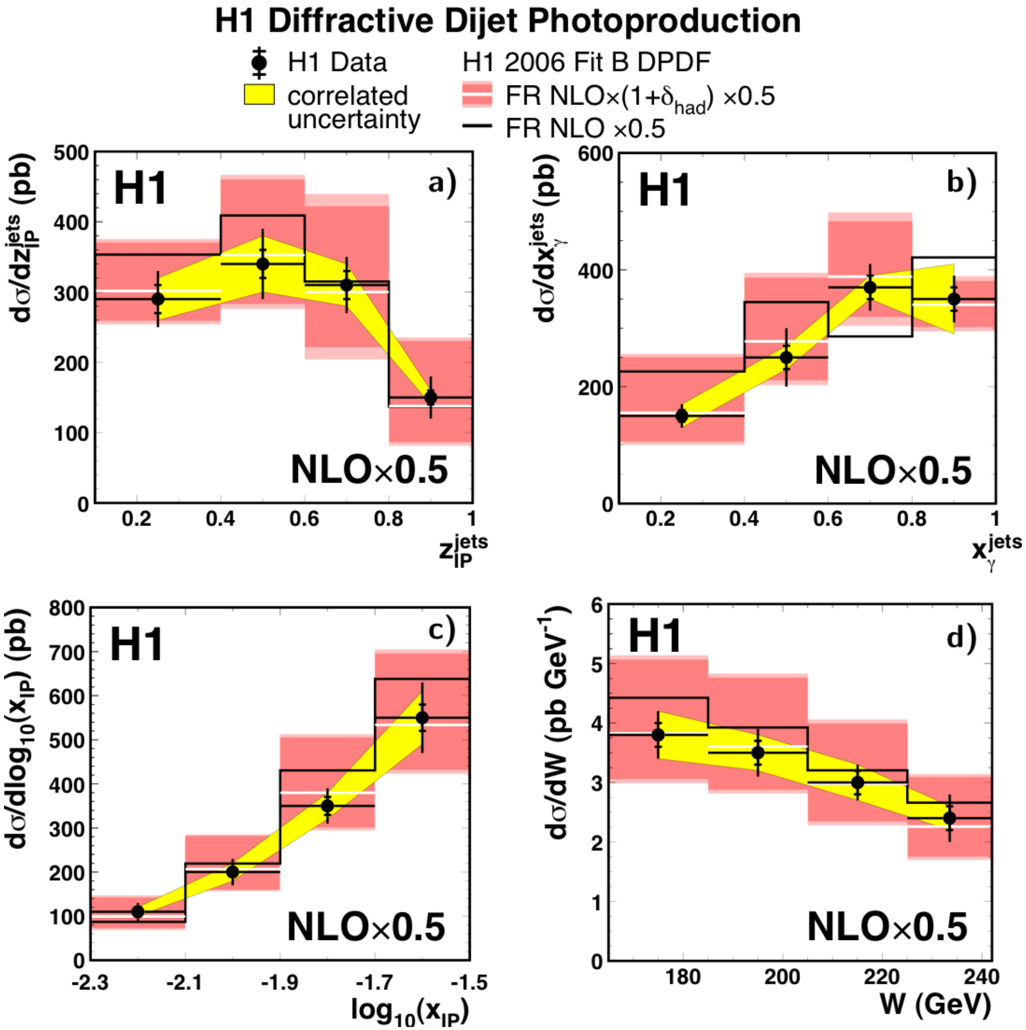
- **Factorisation is broken**
- suppression factor **0.5**, independent of x_{γ}
- direct and resolved photon processes equally suppressed

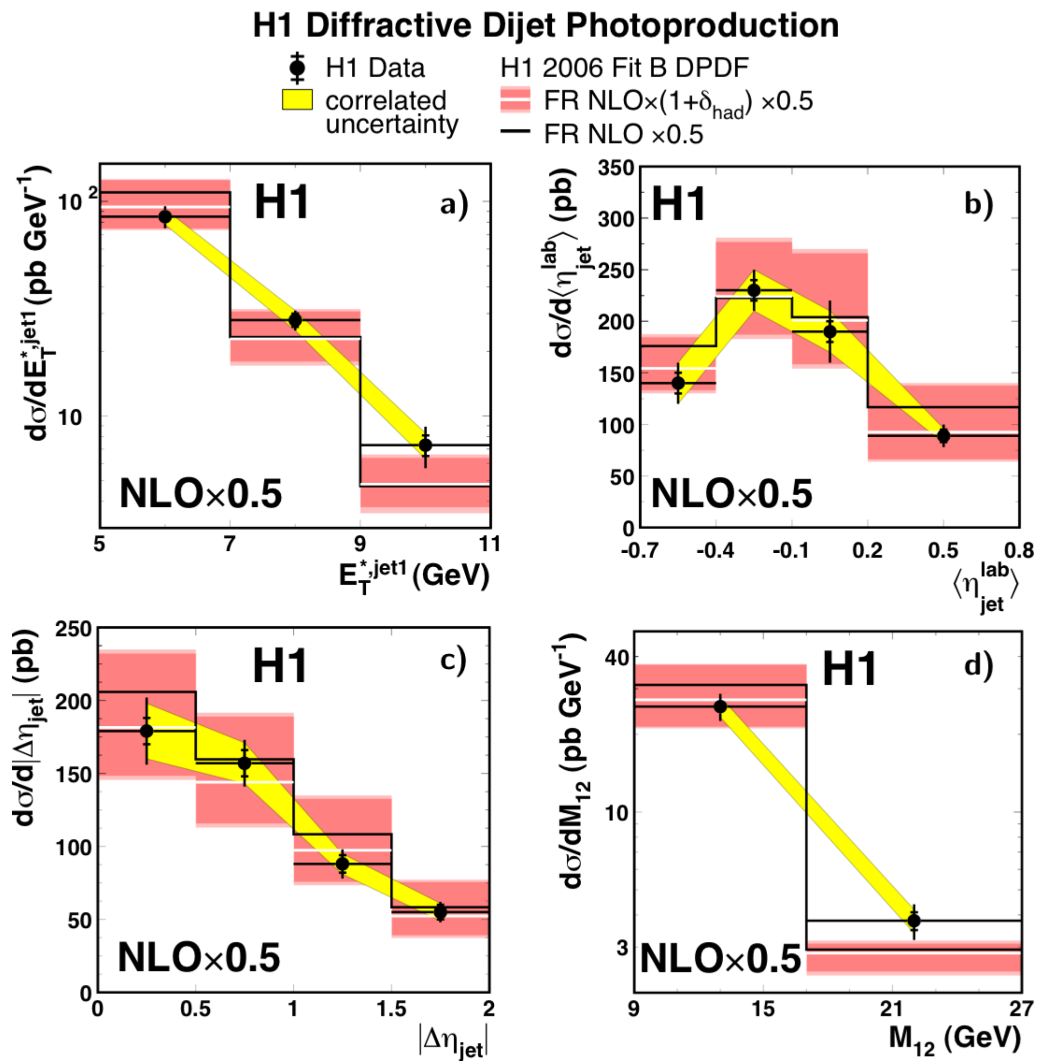
- NLO prediction using private diffractive extension of Frixione/Ridolfi program



$E_T(1)>5$ GeV
$E_T(2)>4$ GeV
$Q^2<0.01$ GeV^2
$x_{IP}<0.03$
$165<W<242$ GeV
18 pb^{-1}

- photon density: GRV-HO (gives best description of inclusive γp dijets)



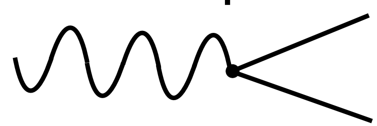


All kinematic variables nicely described with a global gap survival probability of 0.5 (and using Fit B)

Closer look at hadronic photon

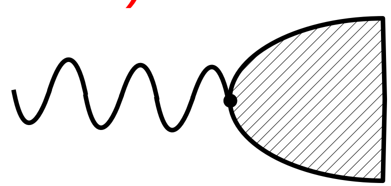
Photon interaction consists of:

- direct
- resolved
    - anomalous part: perturbative photon splitting

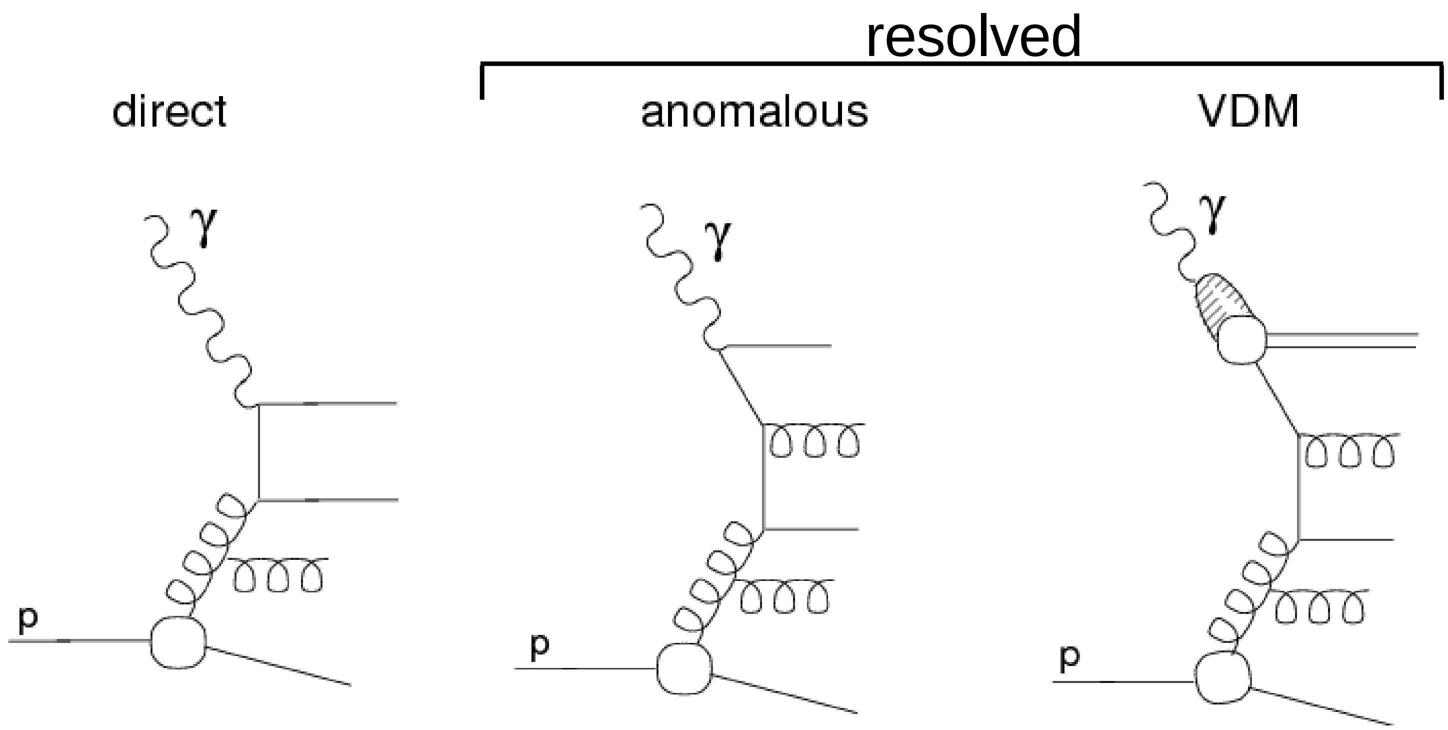


="direct" in higher orders

    - meson contribution (VDM): hadron-like



- expect hadron-like suppression only for meson piece



- direct and anomalous parts connected:

LO anomalous and NLO direct of same order α_s

S Frixione:

separating direct and resolved is unphysical and ill-defined

e.g. leads to huge scale uncertainties of separated parts

- could suppress only VDM part

not yet tried, unclear how to do this technically
(not an option in the NLO programs)

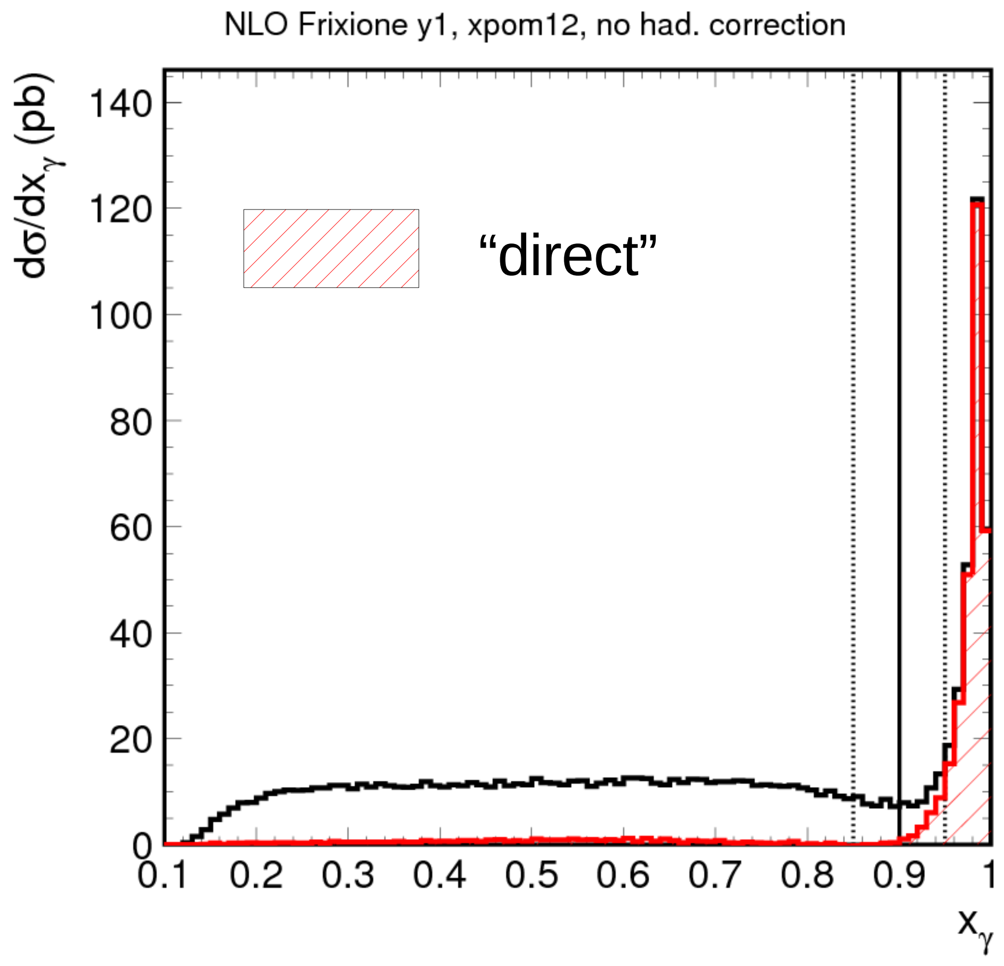
Cut in physical quantity to separate “direct” and “resolved”

“direct”: NLO prediction without photon density
“resolved”: NLO prediction that uses the photon density

$x_\gamma > 0.9$: 85% of “direct”
5% of “resolved”

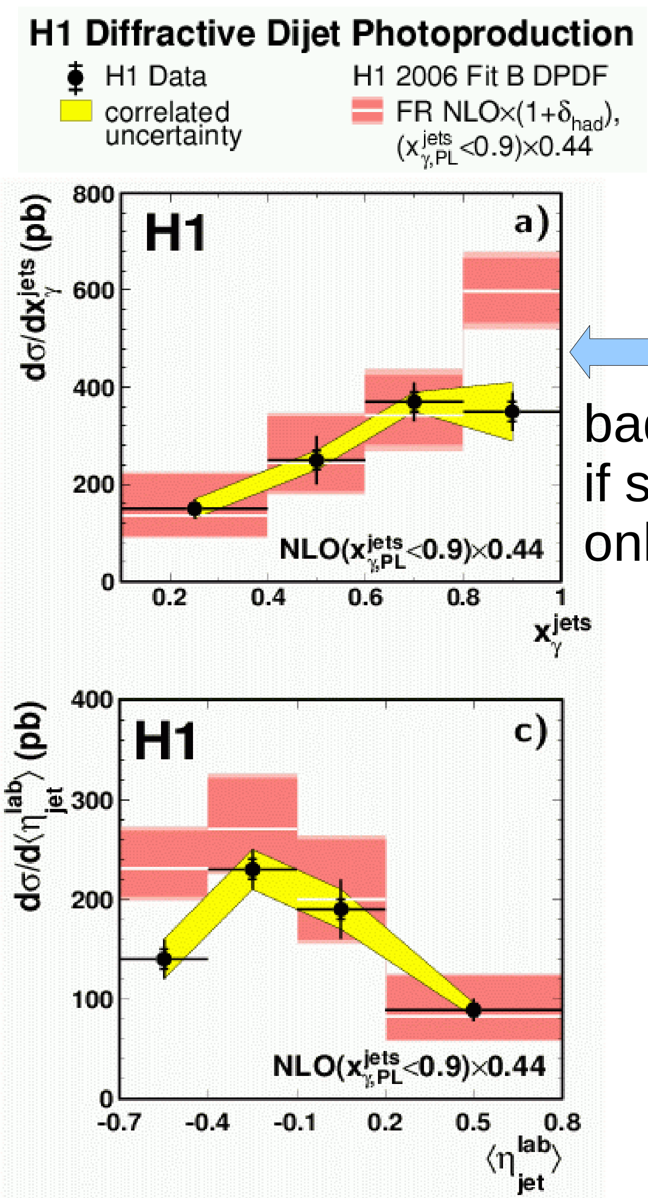
scaling $x_\gamma < 0.9$ is
~ equivalent to
scaling only “resolved”

- variation of cut between 0.85..0.95 changes highest x_γ bin by ±10%



Also “direct” part has to be suppressed!

- At NLO, direct and resolved not cleanly separable
- use experimentalist's approach based on x_γ(parton level)



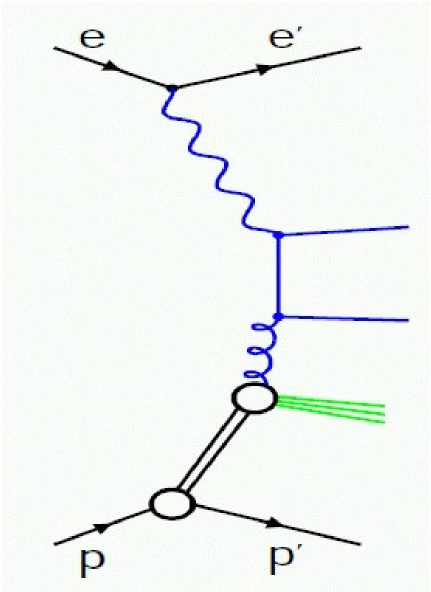
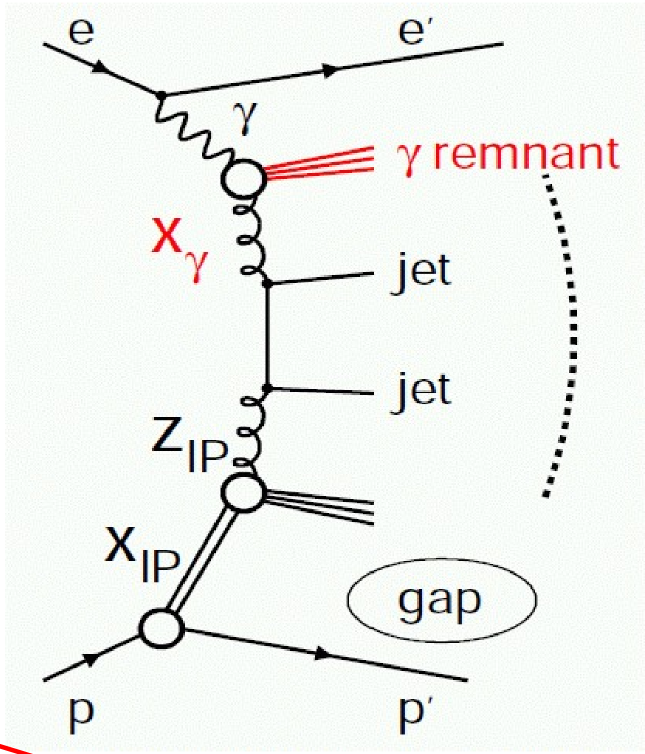
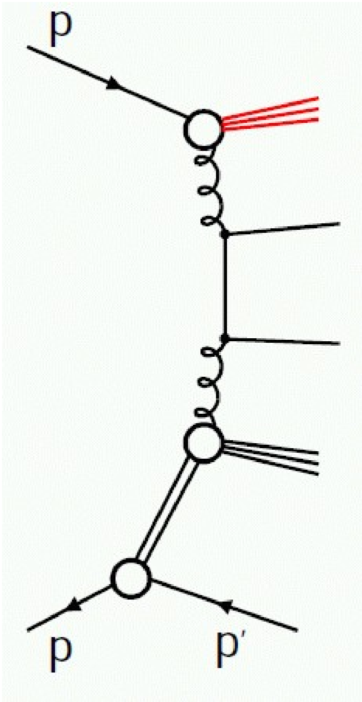
bad description if suppressing only x_γ<0.9

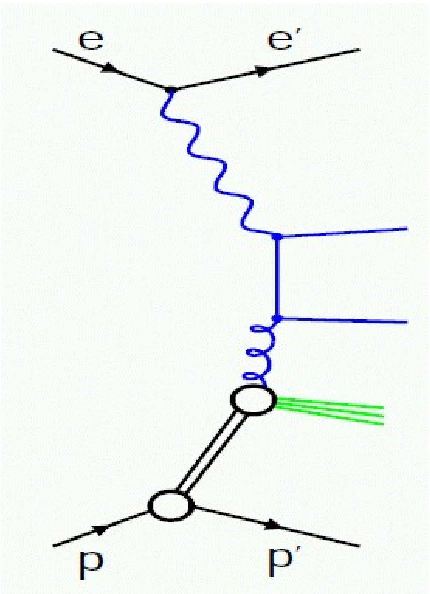
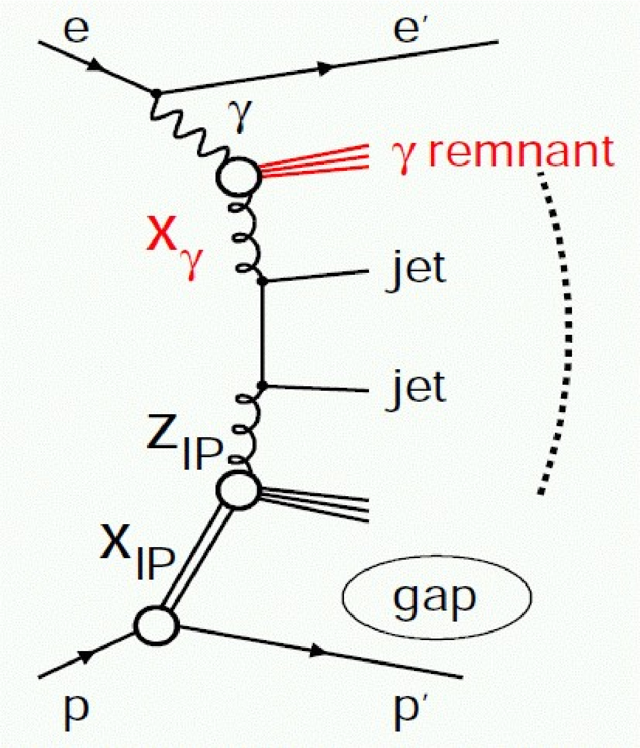
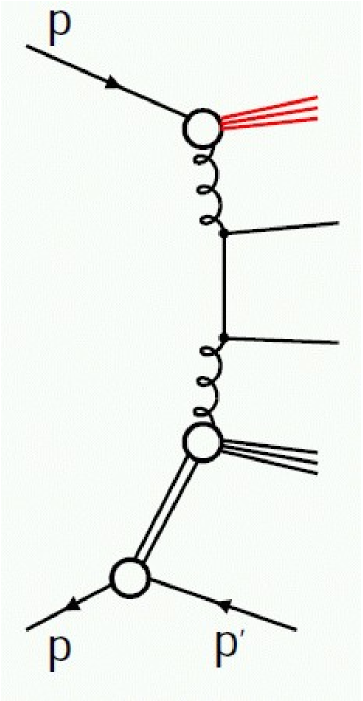
Fit both parts independently:

x_γ(parton level)	Suppression
<0.9	0.47(16)
>0.9	0.53(14)

Suppression independent of x_γ

direct and resolved photon processes equally suppressed (within precision)

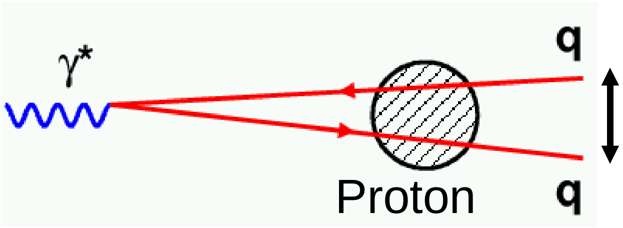
ep	γp	$p\bar{p}$
		
	~~x_γ<1: photon remnant~~ ~~$x_\gamma \approx$1: no remnant~~	proton remnant
Factorisation works	Factorisation broken	Factorisation broken

ep	γp	$p\bar{p}$
		
$Q^2 > 4$ GeV^2	$Q^2 \approx 0$	
Factorisation works	Factorisation broken	Factorisation broken

Is the virtuality the key?

Dipole scattering

in proton rest frame:



$R \sim 1/Q$

	Q^2	dipole	Factorisation	
ep	large	small	works	colour transparency
γp	0	large	broken	colour fields overlap → rescattering

rescattering depends on overlap
of dipole and proton colour fields?

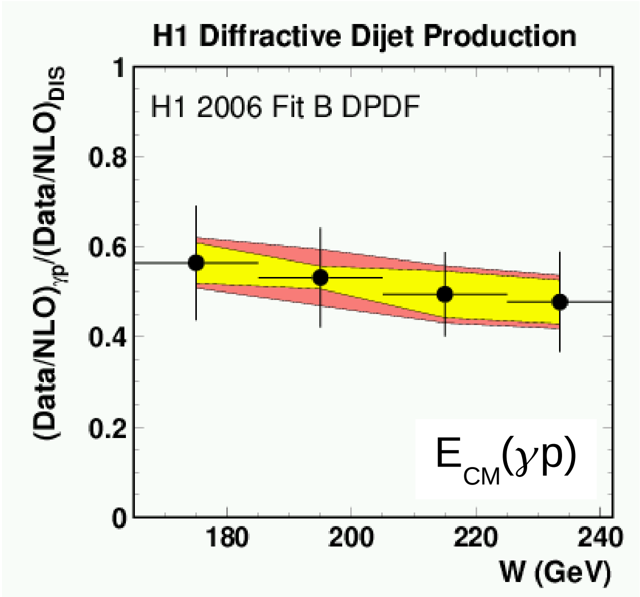
Gap Survival in diffractive γp dijets

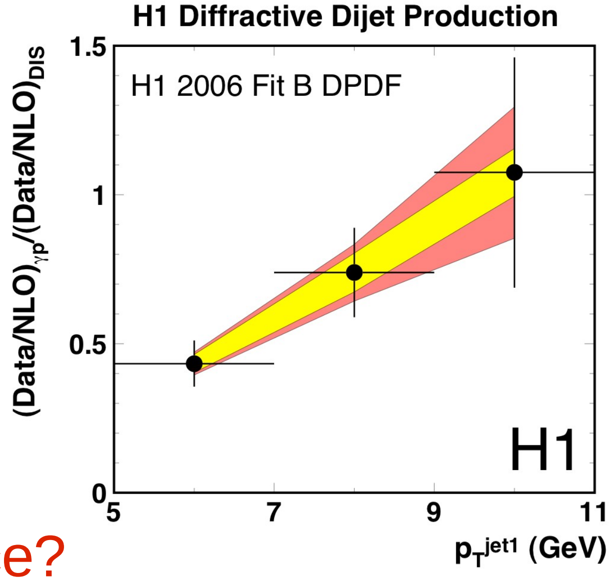
best variable is the **double ratio** of dijet cross sections:

$$\frac{\text{Data/NLO}\ (\gamma p)}{\text{Data/NLO}\ (ep)} = 0.5 \pm 0.1$$

- identical kinematic range
- same data set
- same diffractive parton densities

Advantages:
- some theoretical and experimental uncertainties cancel
- independent of used densities





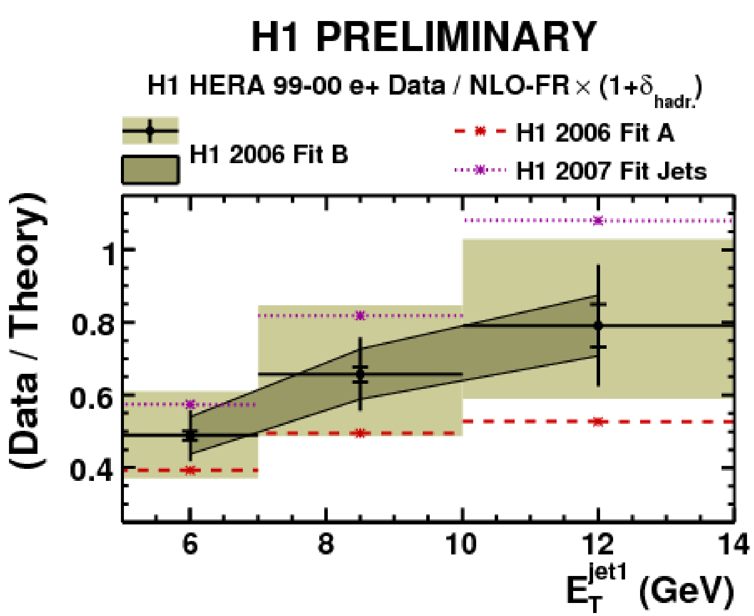
p_T dependence?

uncertainties too large to draw firm conclusion

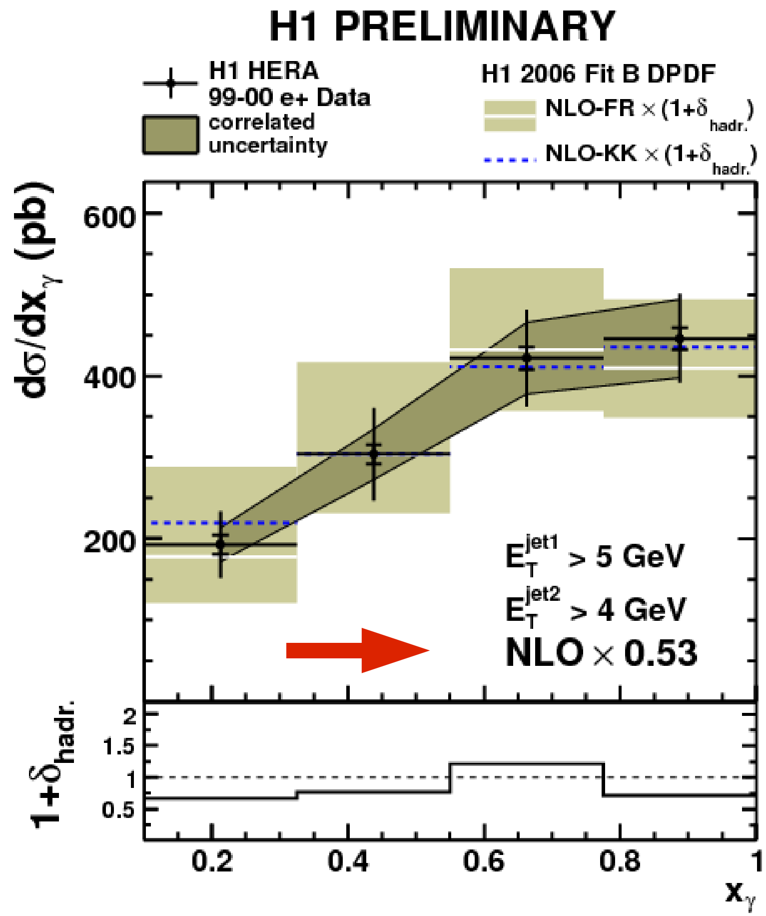
New H1 γp dijet data

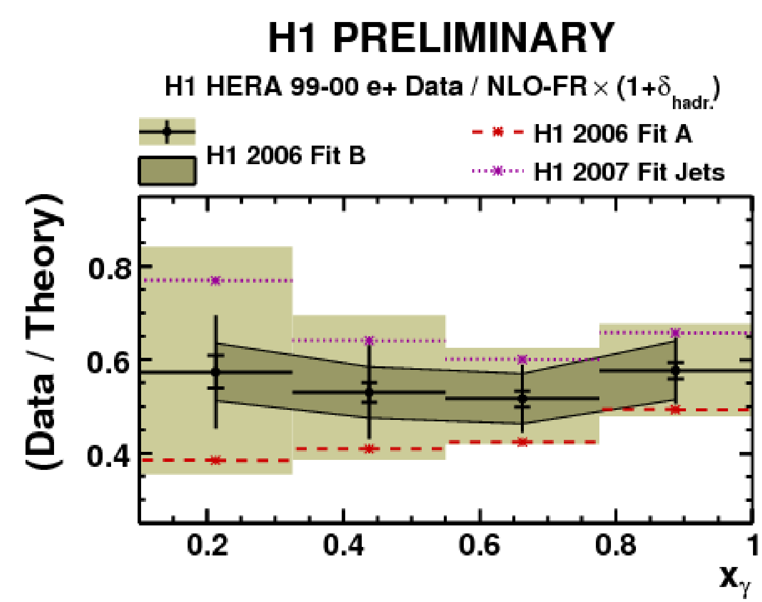
- **Suppression 0.5 confirmed**
- independent NLO Calculation by Klasen and Kramer
- see a trend in p_T for Data/NLO but large errors, no firm conclusion

Note: no double ratio!



$E_T(1)>5$ GeV
$E_T(2)>4$ GeV
$Q^2<0.01$ GeV^2
$x_{IP}<0.03$
$165<W<242$ GeV
54 pb^{-1}





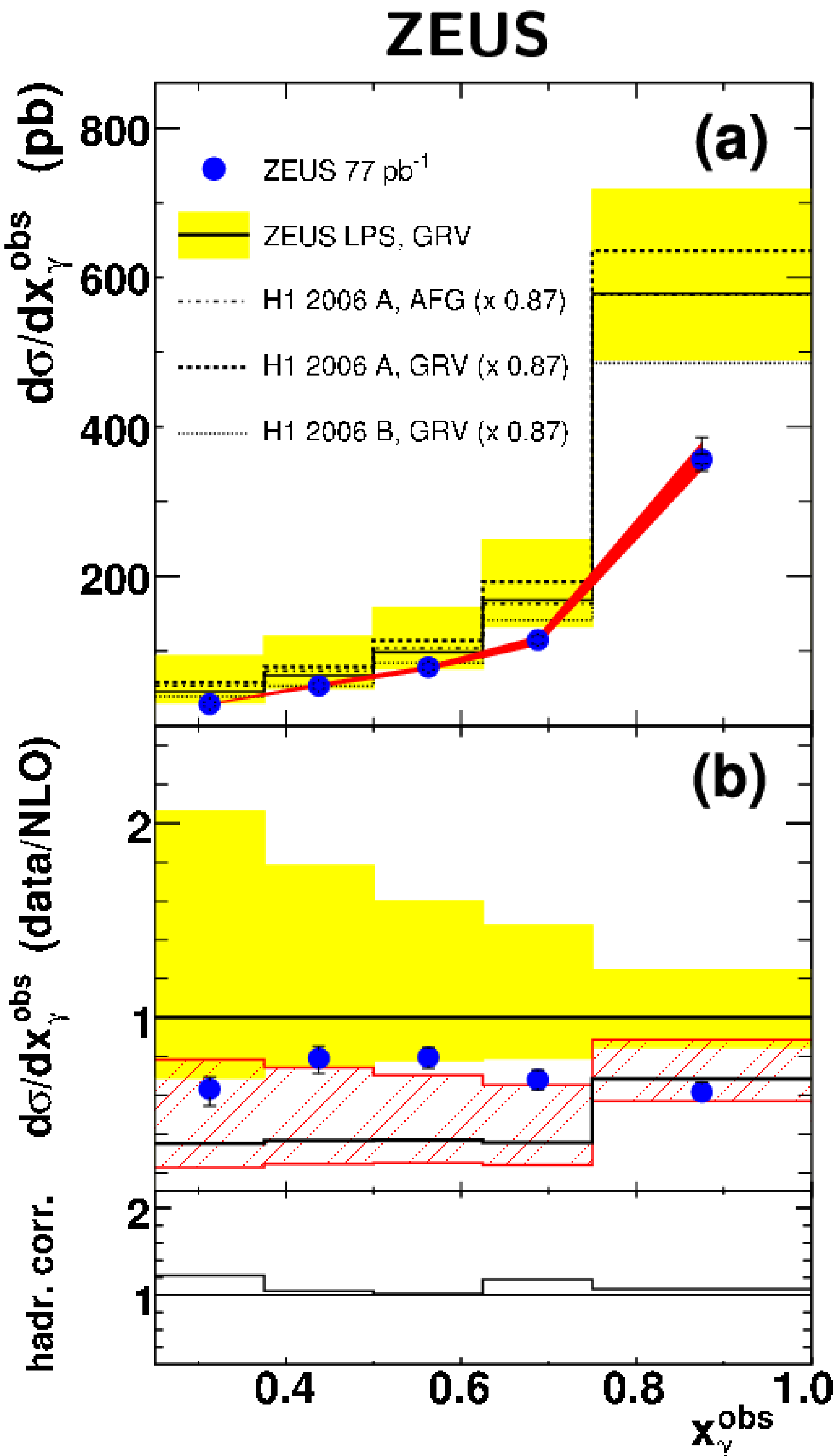
ZEUS analysis

arXiv:0710.1498 [hep-ex]

$E_T(1)>7.5$ GeV
$E_T(2)>6.5$ GeV
$Q^2<1$ GeV^2
$x_{IP}<0.025$
143<W<295 GeV
77 pb^{-1}

- At higher p_T than H1,
- see less suppression, flat in x_γ
- consistent with no suppression within errors

Note: no double ratio!



Summary of diffractive γp dijets

- γp dijets E_T>5 GeV are suppressed by 0.5±0.1 w.r.t. to ep dijets (double ratio)
- the suppression is flat in x_γ
- **the suppression is real and significant**
  - two independent data sets and analyses
  - two independent calculations

- a trend is observed that the suppression goes away at higher E_T
  - no firm conclusion because the errors (data and NLO) are large
  - use double ratio to cancel some of the errors
  - hope for more precise predictions and data
  - would fit in well with dipole picture (size given by Q and E_T)

Collins' Factorisation Proof

- factorisation requires large scale

PSU/TH/189
hep-ph/9709499

Proof of Factorization for Diffractive Hard Scattering

John C. Collins*
Penn State University, 104 Davey Lab, University Park PA 16802, U.S.A.
(September 6, 1999)

Abstract

A proof is given that hard-scattering factorization is valid for deep-inelastic processes which are diffractive or which have some other condition imposed on the final state in the target fragmentation region.

page 3:

$$F_2^{(D)}(x_{\rm bj}, Q, x_{\mathbb{P}}, t) = \sum_i C_{2i} \otimes f_i^D + \text{non-leading power of } Q. \qquad (1)$$

Here, $x_{\rm bj}$ and Q are the usual deep-inelastic variables, $x_{\mathbb{P}} = 1 - q \cdot p'/q \cdot p$ is the fractional loss of longitudinal momentum by the diffracted proton[4], and $t = (p - p')^2$ is the invariant momentum transfer from the diffracted proton, while $\otimes$ signifies a convolution of the hard-scattering coefficient C_{2i} with the diffractive parton density f_i^D. The factorization theorem applies when Q is made large while $x_{\rm bj}$, $x_{\mathbb{P}}$, and t are held fixed. It asserts not only that an expansion of the form of Eq. (1) is true, but also that

- C_{2i} is the *same* hard scattering coefficient as in ordinary (inclusive) deep-inelastic

factorisation breaking at high x_γ, Q≈0, low E_T is not in contradiction with this proof!

Dijet Factorisation Tests Summary

using parton densities extracted in
inclusive diffractive ep scattering

	fact^n	gap survival probability
ep	✔	1
γp	↯	0.5
pp	↯	0.1

E_T>5 GeV, flat in x_γ, trend in E_T

No model I know of can reproduce these numbers and x_γ behaviour

D* Meson (charm) Production in diffractive ep collisions

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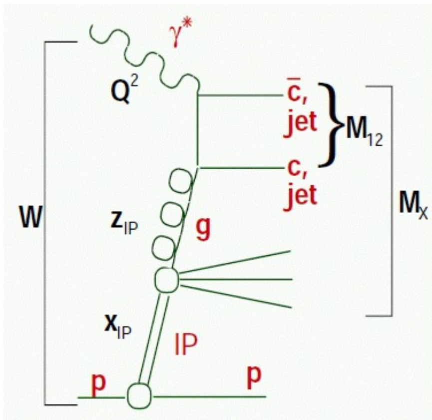
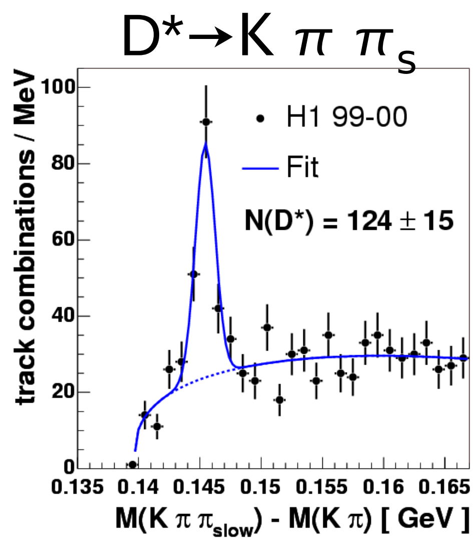
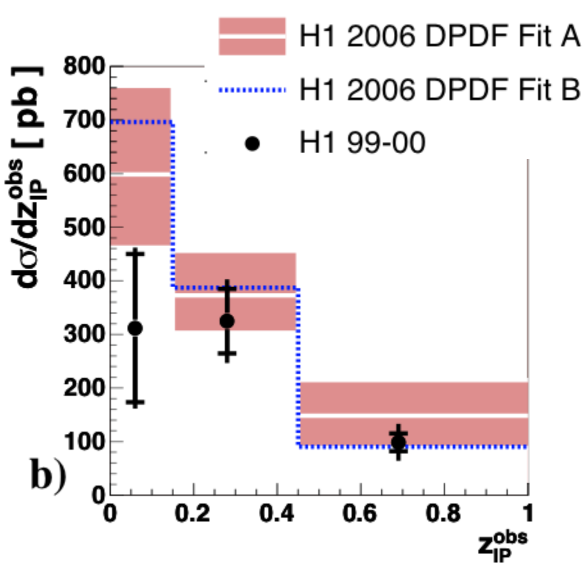
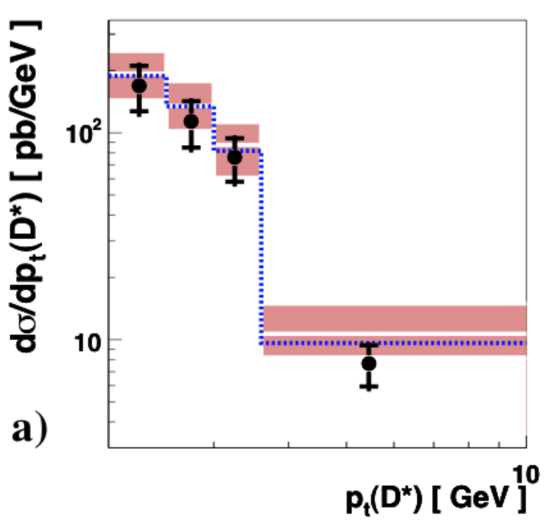




$p_T(D^*)$>2 GeV
$2<Q^2<100$ GeV^2
$x_{IP}<0.04$
$0.05<y<0.7$
47 pb^{-1}

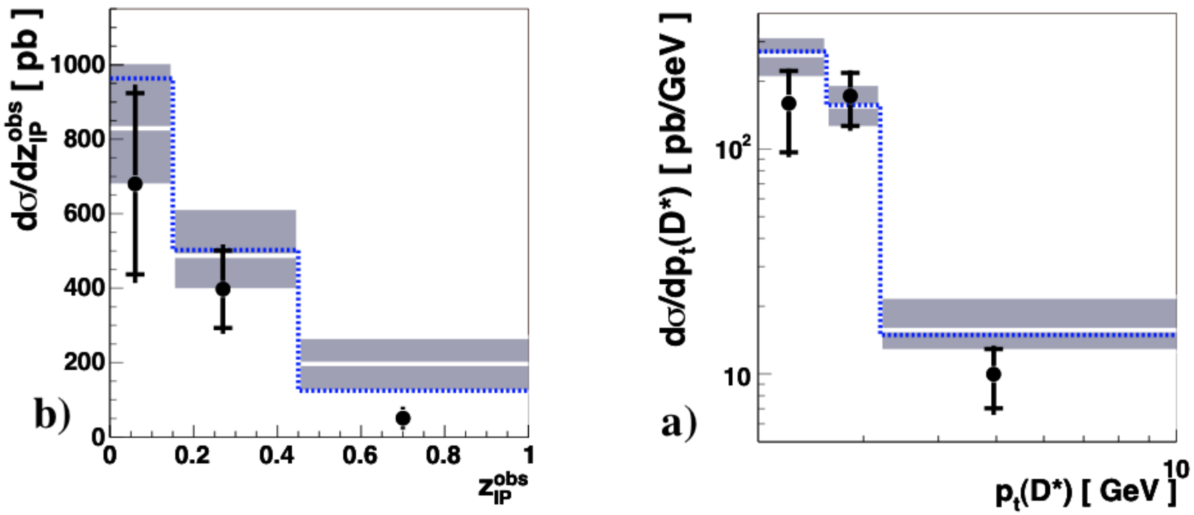




- NLO massive calculation (HVQDIS)
- scale=sqrt($4m_c^2+Q^2$)

Good description, supports QCD factorisation

D* Meson production in diffractive γp collisions



$p_T(D^*)>2$ GeV
$Q^2<0.01$ GeV^2
$x_{IP}<0.04$
$0.3<y<0.65$
47 pb^{-1}

Double ratio (same kinematic range)

$$\frac{\text{Data/NLO} \quad (\gamma p)}{\text{Data/NLO} \quad (ep)} = 1.15 \pm 0.40$$

- consistent with factorisation
- but large uncertainties (statistical)

Diffraction?

So far (in this talk) we have parameterised our ignorance of how diffraction occurs in terms of diffractive parton densities.

Alternatives?

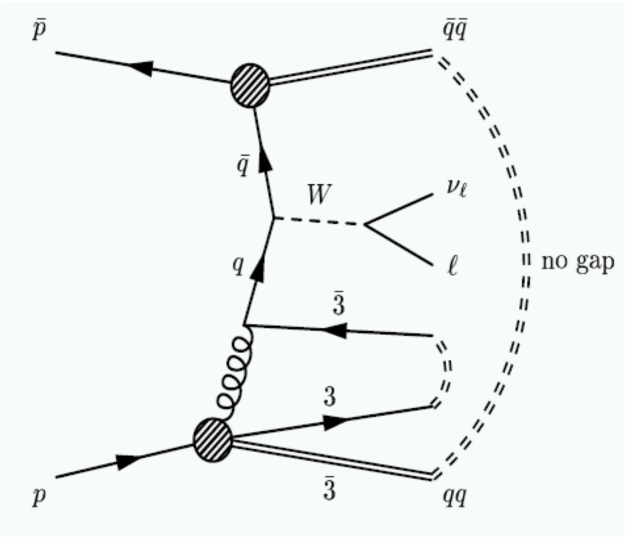
Soft Colour Reconfiguration

SCI Model by Edin, Ingelman, Rathsman

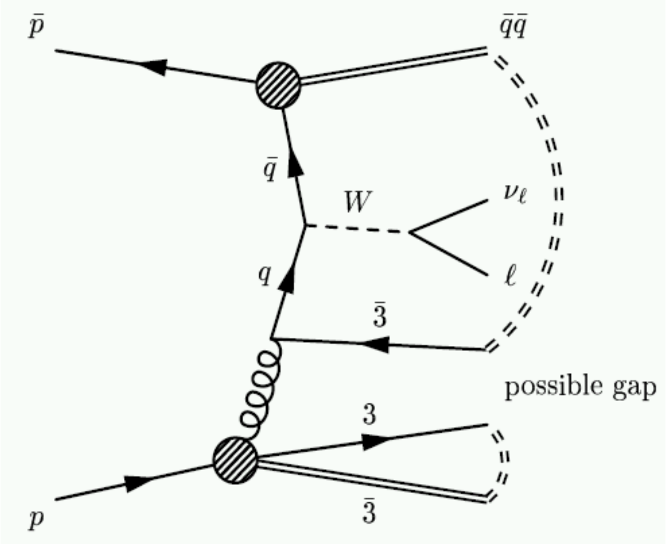
ordinary QCD scattering + final state soft colour reconfiguration

Example: W production in $p\bar{p}$ collisions

ordinary scattering



+ soft colour interactions



1 parameter: colour rearrangement probability, tuned to HERA F_2^D

→ describes diffractive Tevatron data (gap survival ≈0.1)!

Soft Colour Interaction vs. HERA Dijets

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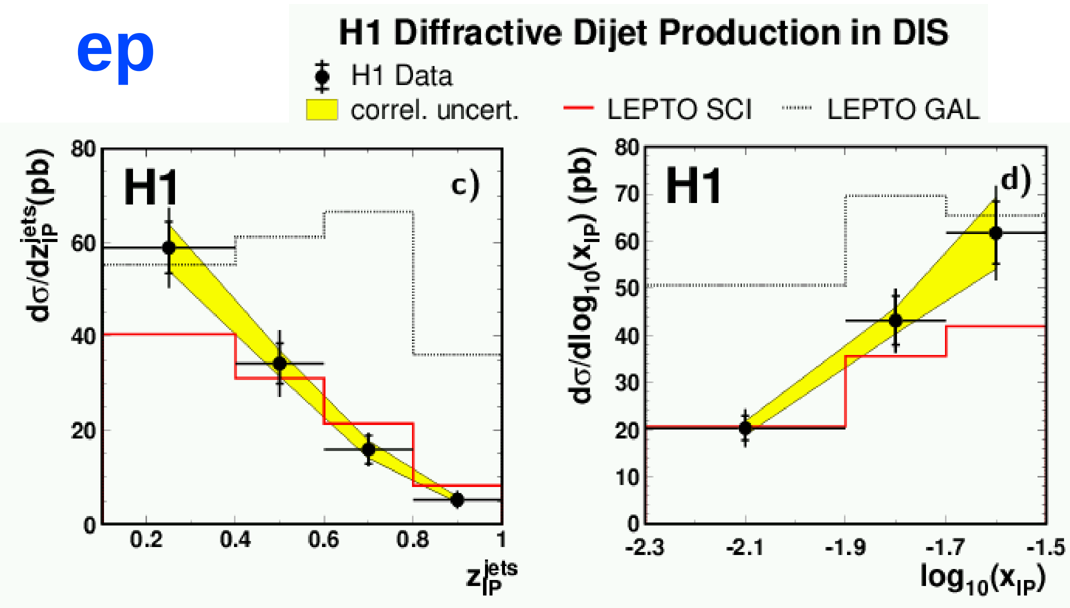
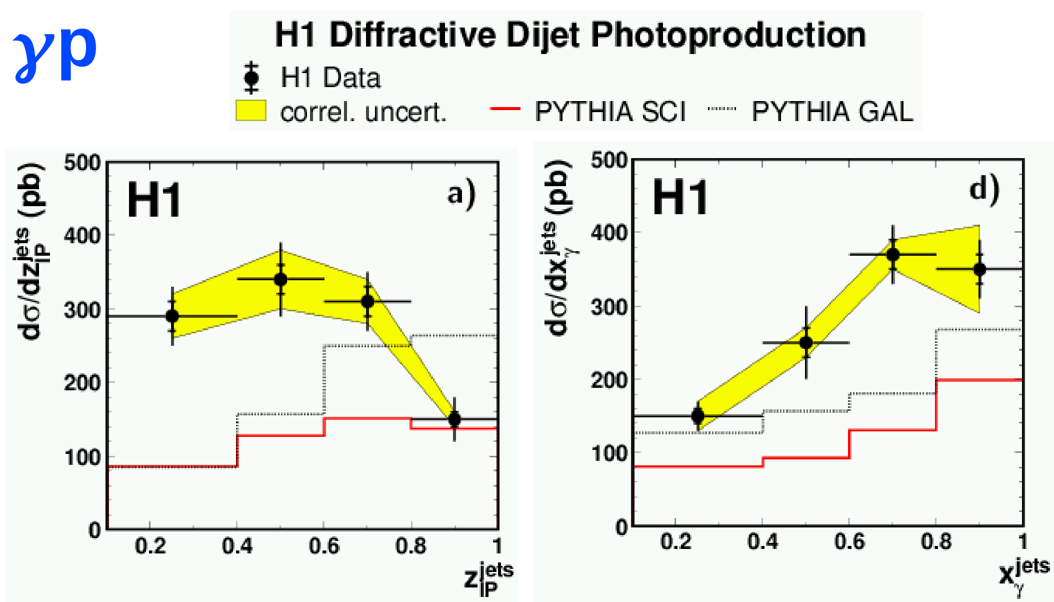
ep



γp



- Leading-order results using LEPTO and PYTHIA (+parton showers)
- proton structure: CTEQ5L LO PDF
- SCI
  - reasonable description for ep
  - fails for γp
- GAL (refined SCI) fails for both ep and γp

H1 Heidelberg Group (Franz Eisele)

- Frank-Peter Schilling (now CMS)
  ep dijets: analysis, NLO calculations; NLO fit to structure functions
- Sebastian Schätzel (now ATLAS)
  γp and ep dijets: analyses, NLO calculations
- Roger Wolf (now CMS)
  γp and ep D*: analyses, NLO calculations
- Matthias Mozer (now CMS)
  ep dijets: analysis, NLO calculations; combined NLO fit to structure functions and dijets
- Stefan Schenk (now BaBar)
  rapidity gap selection efficiency from tagged protons

all NLO calculations, fits using existing programs, but extended to diffraction

Summary

- understanding diffraction is a principal unsolved problem within the Standard Model
- a wealth of diffractive HERA measurements is published
- factorisation breaking is established and quantified in γp vs. ep diffractive dijet production
  - resolved and direct photon processes are equally suppressed by a factor 0.5±0.1
- now we need models and theories which respect these data!